David S. Bachman. 95

David S. Bachman. '95

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ELEMENTARY TREATISE

ON

NATURAL PHILOSOPHY.

BY

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IN FOUR PARTS.

PART III.

ELECTRICITY AND MAGNETISM.

ILLUSTRATED BY

260 ENGRAVINGS ON WOOD, AND ONE COLORED PLATE.

TENTH EDITION.

NEW YORK:

D. APPLETON AND COMPANY,

1, 3, AND 5 BOND STREET.

1891.

PREFACE TO THE TENTH EDITION OF

PART III.

THIS Part, even in its original form, was to a great extent rewritten rather than translated from the French. In the sixth edition it received important modifications, especially in the department of Current Electricity, in which there was a complete rearrangement of subjects. A collection of Examples, with answers, was at the same time added. In the seventh and eighth editions new matter was introduced under the heads of Storage Batteries, Selenium Cell and Photophone, Dynamo Machines, Incandescent Electric Lamps, Voss Machine, and Quadruplex Telegraphy. The ninth edition gave a fuller account of the Voss Machine, with illustration, an investigation relative to the work done in moving charged conductors, with application to Thomson's Quadrant Electrometer, and a table of Electro-chemical Equivalents. The tenth edition contains a much fuller account of the theory of Thermo-electricity, some additions relating to electrical Transmission of Power, and later information respecting Specific Inductive Capacity, and modern Electrical Machines.

BELFAST, *November*, 1888.

NOTE PREFIXED TO FIRST EDITION.

THE accurate method of treating electrical subjects which has been established in this country by Sir Wm. Thomson and his coadjutors, has not yet been adopted in France; and some of Faraday's electro-magnetic work appears to be still very imperfectly appreciated by French writers. The Editor has accordingly found it necessary to recast a considerable portion of the present volume, besides introducing two new chapters and an Appendix. Potential and lines of force are not so much as mentioned in the original.

The elements of the theory of magnetism have been based on Sir Wm. Thomson's papers in the *Philosophical Transactions;* and the description of the apparatus used in magnetic observatories has been drawn from the recently published work of the Astronomer Royal. The account of electrical units given in the Appendix is mainly founded on the Report of the Electrical Committee of the British Association for the year 1863.

M. Deschanel's descriptions of apparatus, of which some very elaborate examples occur in the present volume, left little to be desired in point of clearness. In no instance has it been found necessary to resort to the mere verbal rendering of unintelligible details.

CONTENTS—PART III.

THE NUMBERS REFER TO THE SECTIONS.

ELECTRICITY.

CURRENT ELECTRICITY.

Chapter LIII. GALVANIC BATTERY.

Chapter LIV. GALVANOMETER.

Chapter LV. ELECTRO-CHEMISTRY.

Chapter LVI. OHM'S LAW.

Chapter LVII. RELATIONS BETWEEN ELECTRICITY AND HEAT.

Chapter LVIII. ELECTRO-DYNAMICS.

Chapter LIX. INDUCTION OF CURRENTS.

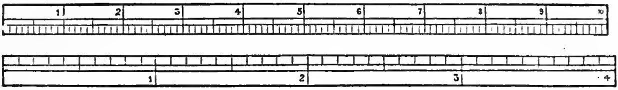
Chapter LX. ELECTRIC TELEGRAPHS.

Chapter LXI. MISCELLANEOUS APPLICATIONS OF ELECTRICITY.

Appendix. ELECTRICAL AND MAGNETIC UNITS.

FRENCH AND ENGLISH MEASURES.

A DECIMETRE DIVIDED INTO CENTIMETRES AND MILLIMETRES.



INCHES AND TENTHS.

REDUCTION OF FRENCH TO ENGLISH MEASURES.

Length.

1 millimetre = ·03937 inch, or about $\frac{1}{25}$ inch.
1 centimetre = ·3937 inch.
1 decimetre = 3·937 inch.
1 metre = 39·37 inch = 3·281 ft. = 1·0936 yd.
1 kilometre = 1093·6 yds., or about $\frac{5}{8}$ mile.
More accurately, 1 metre = 39·370432 in. = 3·2808693 ft. = 1·09362311 yd.

Area.

1 sq. millim. = ·00155 sq. in.
1 sq. centim. = ·155 sq. in.
1 sq. decim. = 15·5 sq. in.
1 sq. metre = 1550 sq. in. = 10·764 sq. ft. = 1·196 sq. yd.

Volume.

1 cub. millim. = ·000061 cub. in.
1 cub. centim. = ·061025 cub. in.
1 cub. decim. = 61·0254 cub. in.
cub. metre = 61025 cub. in. = 35·3156 cub. ft. = 1·308 cub. yd.

The Litre (used for liquids) is the same as the cubic decimetre, and is equal to 1·7617 pint, or ·22021 gallon.

Mass and Weight.

1 milligramme = ·01543 grain.
1 gramme = 15·432 grain.
1 kilogramme = 15432 grains = 2·205 lbs. avoir.
More accurately, the kilogramme is 2·20462125 lbs.

Miscellaneous.

1 gramme per sq. centim. = 2·0481 lbs. per sq. ft.
1 kilogramme per sq. centim. = 14·223 lbs. per sq. in.
1 kilogrammetre = 7·2331 foot-pounds.
1 force de cheval = 75 kilogrammetres per second, or 542½ foot-pounds per second nearly, whereas 1 horse-power (English) = 550 foot-pounds per second.

REDUCTION TO C.G.S. MEASURES. (See page 48.)

[*cm.* denotes centimetre(s); *gm.* denotes gramme(s).]

Length.

1 inch = 2·54 centimetres, nearly.
1 foot = 30·48 centimetres, nearly.
1 yard = 91·44 centimetres, nearly.
1 statute mile = 160933 centimetres, nearly.
More accurately, 1 inch = 2·5399772 centimetres.

Area.

1 sq. inch = 6·45 sq. cm., nearly.
1 sq. foot = 929 sq. cm., nearly.
1 sq. yard = 8361 sq. cm., nearly.
1 sq. mile = $2·59 \times 10^{10}$ sq. cm., nearly.

Volume.

1 cub. inch = 16·39 cub. cm., nearly.
1 cub. foot = 28316 cub. cm., nearly.
1 cub. yard = 764535 cub. cm., nearly.
1 gallon = 4541 cub. cm., nearly.

Mass.

1 grain = ·0648 gramme, nearly.
1 oz. avoir. = 28·35 gramme, nearly.
1 lb. avoir. = 453·6 gramme, nearly.
1 ton = $1·016 \times 10^6$ gramme, nearly
More accurately, 1 lb. avoir. = 453·59265 gm.

Velocity.

1 mile per hour = 44·704 cm. per sec.
1 kilometre per hour = 27·7 cm. per sec.

Density.

1 lb. per cub. foot = ·016019 gm. per cub. cm.
62·4 lbs. per cub. ft. = 1 gm. per cub. cm.

FORCE (assuming $g=981$). (See p. 48.)

Weight of 1 grain $=63\cdot57$ dynes, nearly.
" 1 oz. avoir. $=2\cdot78\times10^4$ dynes, nearly.
" 1 lb. avoir. $=4\cdot45\times10^5$ dynes, nearly.
" 1 ton $=9\cdot97\times10^8$ dynes, nearly.
" 1 gramme $=981$ dynes, nearly.
" 1 kilogramme $=9\cdot81\times10^5$ dynes, nearly.

WORK (assuming $g=981$). (See p. 48.)

1 foot-pound $=1\cdot356\times10^7$ ergs, nearly.
1 kilogrammetre $=9\cdot81\times10^7$ ergs, nearly.
Work in a second by one theoretical "horse." $=7\cdot46\times10^9$ ergs, nearly.

STRESS (assuming $g=981$).

1 lb. per sq. ft. $=479$ dynes per sq. cm., nearly.
1 lb. per sq. inch $=6\cdot9\times10^4$ dynes per sq. cm., nearly.
1 kilog. per sq. cm. $=9\cdot81\times10^5$ dynes per sq. cm., nearly.
760 mm. of mercury at 0°C. $=1\cdot014\times10^6$ dynes per sq. cm., nearly.
30 inches of mercury at 0° C. $=1\cdot0163\times10^6$ dynes per sq. cm., nearly.
1 inch of mercury at 0° C. $=3\cdot388\times10^4$ dynes per sq. cm., nearly.

TABLE OF CONSTANTS.

The velocity acquired in falling for one second in vacuo, in any part of Great Britain, is about 32·2 feet per second, or 9·81 metres per second.

The pressure of one atmosphere, or 760 millimetres (29·922 inches) of mercury, is 1·033 kilogramme per sq. centimetre, or 14·73 lbs. per square inch.

The weight of a litre of dry air, at this pressure (at Paris) and 0° C., is 1·293 gramme.

The weight of a cubic centimetre of water is about 1 gramme.

The weight of a cubic foot of water is about 62·4 lbs.

The equivalent of a unit of heat, in gravitation units of energy, is—

772 for the foot and Fahrenheit degree.
1390 for the foot and Centigrade degree.
424 for the metre and Centigrade degree.
42400 for the centimetre and Centigrade degree.

In absolute units of energy, the equivalent is—

41·6 millions for the centimetre and Centigrade degree;

1 gramme-degree is equivalent to 41·6 million ergs.

UNITS EMPLOYED BY PRACTICAL ELECTRICIANS.

The *ohm* is (or was intended to be) 10^9 C. G. S. electro-magnetic units of resistance.

The *volt* is 10^8 C. G. S. electro-magnetic units of electro-motive force.

The *ampère* is $\frac{1}{10}$ of the C. G. S. electro-magnetic unit of current, and is the current produced by an electro-motive force of 1 volt in a circuit whose resistance is 1 ohm.

The *coulomb* is $\frac{1}{10}$ of the C. G. S. electro-magnetic unit of quantity, and is the quantity conveyed in 1 second by a current of 1 ampère.

The *farad* is 10^{-9} of the C. G. S. electro-magnetic unit of capacity, and the *microfarad* is the millionth part of the farad. A charge of 1 coulomb given to a condenser of capacity 1 farad would raise its potential by 1 volt.

The *watt* is 10^7 ergs per second, and is the rate at which work is done by 1 ampère traversing 1 ohm.

The *joule* is 10^7 ergs.

ELECTRICITY.

CHAPTER XLI.

INTRODUCTORY PHENOMENA.

556. Fundamental Phenomena.—If a glass tube be rubbed with a silk handkerchief, both tube and rubber being very dry, the tube will be found to have acquired the property of attracting light bodies. If the part rubbed be held near to small scraps of paper, pieces of

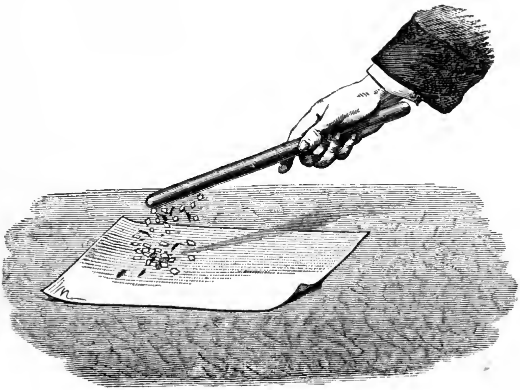


Fig. 332.—Attraction of Light Bodies by an Electrified Body.

cut straw, sawdust, &c., these objects will move to the tube; sometimes they remain in contact with it, sometimes they are alternately attracted and repelled, the intensity as well as the duration of these effects varying according to the amount of friction to which the tube has been subjected.

If the tube be brought near the face, the result is a sensation similar

to that produced by the contact of a cobweb. If the knuckle be held near the tube, a peculiar crackling noise is heard, and a bright *spark* passes between the tube and knuckle. The tube then has acquired peculiar properties by the application of friction. It is said to be *electrified*, and the name of *electricity* is given to the agent to which the various phenomena just described are attributed.

Glass is not the only substance which can be electrified by friction; the same property is possessed also by resin, sulphur, precious stones, amber, &c. The Greek name of this last substance (ἤλεκτρον) is the root from which the word *electricity* is derived.

At first sight it appears that this property of becoming electrified by friction is not common to all bodies; for if a bar of metal be held in the hand and rubbed with wool, it does not acquire the properties

Fig. 333.—Electrification of a Metal by Friction

of an electrified body. But we should be wrong in concluding that metals cannot be electrified by friction; for if the bar be fitted on to a glass rod, and, while held by this handle, be struck with flannel or catskin, it may be very sensibly electrified. There is therefore no basis for the distinction formerly made between electrics and non-electrics, that is, between substances capable and incapable of being electrified by friction; for all bodies, as far as at present known, are capable of being thus excited. There is, however, an important difference of another kind between them, which was first pointed out by Stephen Grey in 1729.

557. Conductors and Non-conductors.—In certain bodies, such as glass and resin, electricity does not spread itself beyond the parts of the surface where it has been developed; while in other bodies, such as metals, the electricity developed at any point immediately spreads itself over the whole body. Thus, in the last-mentioned experiment, the signs of electricity are immediately manifested at the end of the metal bar which is farthest from the glass rod, if the end next the rod be submitted to friction. Bodies of the former kind, such as glass, resin, &c., are said to be *non-conductors*. Metals are said to be good *conductors*. A non-conductor is often called an *insulator*, and a conductor supported by a non-conductor is said to be *insulated*. The appropriateness of these expressions is evident. No substance is perfectly non-conducting, but the difference in conduct-

ing power between what are called non-conductors and good conductors, is enormous. The following are lists of conductors and non-conductors, arranged, at least approximately, in order of their conducting powers. In the list of conductors, the best conductors are put first; in the list of non-conductors, the worst conductors (or best insulators) are put first.

CONDUCTORS.

All metals.	Metallic ores.	Living vegetables.
Well-burned charcoal.	Animal fluids.	Flax.
Plumbago.	Sea water.	Hemp.
Concentrated acids.	Spring water	Living animals.
Dilute acids.	Rain water.	Flame.
Saline solutions.	Snow.	Moist earth and stones.

NON-CONDUCTORS.

Shellac.	Gems.	Leather.
Amber.	Ebonite.	Baked wood.
Resins.	Caoutchouc.	Porcelain.
Sulphur.	Gutta-percha.	Marble.
Wax.	Silk.	Camphor.
Jet.	Wool.	Chalk.
Glass.	Feathers.	Lime.
Mica.	Dry paper.	Oils.
Diamond.	Parchment.	Metallic oxides.

The human body is a good conductor of electricity. If a person standing on a stool with glass legs be struck with a catskin, he becomes electrified in a very perceptible degree, and sparks may be drawn from any part of his body.

When an insulated and electrified conductor is allowed to touch another conductor insulated but not electrified, it is observed that, after the contact, both bodies possess electrical properties, electricity having been communicated to the second body at the expense of the first. If the second body be much the larger of the two, the electricity of the first is greatly diminished, and may become quite insensible. This explains the disappearance of electricity when a body is put in connection with the earth, which, together with most of the objects on its surface, may be regarded as constituting one enormous conductor. On account of its practically inexhaustible capacity for furnishing or absorbing electricity, the earth is often called *the common reservoir*.

It will now be easily understood why it is not possible to electrify a metal rod by rubbing it while it is held in the hand; since the

electricity, as fast as it is generated, passes off through the body into the earth.

Air, when thoroughly dry, is an excellent insulator; and electrified conductors exposed to it, and otherwise insulated, retain their charge with very little diminution for a considerable time. Dampness in the air is, however, a great obstacle to insulation, mainly, or (as it would appear from Sir W. Thomson's experiments) entirely, by reason of the moisture which condenses on the insulating supports. Electrical experiments are accordingly very difficult to perform in damp weather. The difficulty is sometimes met by employing a stove to heat the air in the neighbourhood of the supports, and thus diminish its relative humidity. Sir W. Snow Harris employed heating-irons, which were heated in a fire, and then fixed near the insulating supports; and thus succeeded in exhibiting electrical experiments to an audience in the most unfavourable weather. Sir W. Thomson, by keeping the air in the interior of his electrometers dry by means of sulphuric acid, causes them to retain their charge with only a small percentage of loss in twenty-four hours. Dry frosty days are the best for electrical experiments, and next perhaps to these, is the season of dry cutting winds in spring.

558. Duality of Electricity.—The elementary phenomena which we have mentioned in the beginning of this chapter may be more accurately studied by means of the electric pendulum, which consists of a pith-ball suspended by a silk fibre from an insulated support. When an electrified glass rod is brought near the insulated ball, the latter is attracted; but as soon as it touches the glass tube, the attraction is changed to repulsion, which lasts as long as the ball retains the electricity which it has acquired by the contact. A similar experiment can be shown by employing, instead of the glass tube, any other body which has been electrified by friction, for example, a piece of resin which has been rubbed with flannel.

If, while the pendulum exhibits repulsion for the glass, the electrified resin is brought near, it is attracted by the latter; and conversely, when it is repelled by the resin, it is attracted by the glass. These phenomena clearly show that the electricity developed on the resin is not of the same kind as that developed on the glass. They exhibit opposite forces towards any third electrified body, each attracting what the other repels. They have accordingly received names which indicate opposition. The electricity which glass acquires when rubbed with silk, is called *positive;* and that which resin acquires by friction

with flannel, *negative.* The former is also called *vitreous,* and the latter *resinous.* On repeating the experiment with other substances,

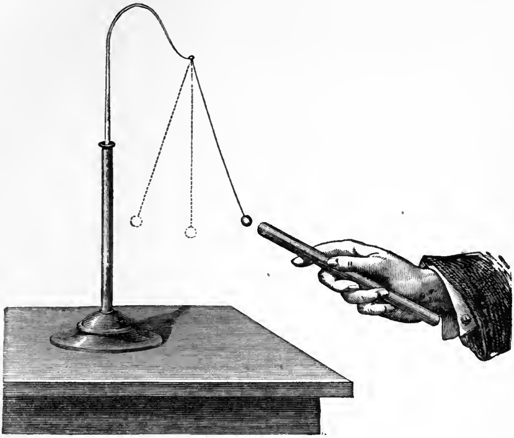


Fig. 334. Electric Pendulum.

it is found that all electrified bodies behave either like the glass or like the resin.

559.—Without making any assumption as to what electricity is, we may speak of an electrified body as being *charged with electricity,* and we may compare quantities of electricity by means of the attractions and repulsions exerted. Bodies oppositely electrified must then be spoken of as charged with *electricities of opposite kind,* or *of opposite sign;* and experiment shows that, whenever electricity of the one kind is developed, whether by friction or by any other means, electricity of the opposite sign is always developed in exactly equal quantity. If a conductor receives two charges of electricity of equal quantity but opposite sign, it is found to exhibit no traces of electricity whatever.

Electricities of like sign repel one another and those of unlike sign attract one another.—The magnitude of the force exerted upon each other by two electrified bodies, is not altered in amount by reversing the sign of the electricity of one or both of them, provided that the quantities of electricity, and their distribution over the two

bodies, remain unchanged. If the sign of one only be changed, the mutual force is simply reversed, and if the signs of both be changed, the force is not changed at all.

560.—The simultaneous development of both kinds of electricity is illustrated by the following experiment:—Two persons stand on stools with glass legs, and one of them strikes the other with a catskin. Both of them are now found to be electrified, the striker positively, and the person struck negatively, and from both of them sparks may be drawn by presenting the knuckle.

The kind of electricity which a body obtains by friction with another body, evidently depends on the nature of their surfaces. If, for example, we take two discs, one of glass, and the other of metal, and, holding them by insulating handles, rub them briskly together, we shall find that the metal becomes negatively, and the glass positively electrified; but if the metal be covered with a catskin, and the experiment repeated, it will be the glass which will this time be negatively electrified. In the subjoined list, the substances are arranged in such order that, generally speaking, each of them becomes positively electrified by friction with those which follow it, and negatively with those which precede it.

Fur of cat.	Feathers.	Silk.
Polished glass.	Wood.	Shellac.
Woollen stuffs.	Paper.	Rough glass.

561. Hypotheses regarding the Nature of Electricity.—Two theories regarding the nature of electricity must be described on account of the historical interest attaching to them.

The two-fluid theory, originally propounded by Dufaye, reduced to a more exact form by Symmer, and still very extensively adopted, maintains that the opposite kinds of electricity are two fluids. Positive electricity is called the *vitreous fluid*, and negative electricity the *resinous fluid.* Fluids of like name repel, and those of unlike name attract each other. The union of equal quantities of the two fluids constitutes the neutral fluid which is supposed to exist in very large quantity in all unelectrified bodies. When a body is electrified, it gains an additional quantity of the one fluid, and loses an equal quantity of the other, so that the total amount of electric fluid in a body is never changed; and (as a consequence of this last condition) when a current of either fluid traverses a body in any direction, an equal current of the other fluid traverses it in the opposite direction.

This theory is in complete agreement with all electrical phenomena so far as at present known; but as it is conceivable that the two electricities, instead of being two kinds of matter, may be two kinds of motion, or, in some other way, may be opposite states of one and the same substance, it is more philosophical to avoid the assumption involved in speaking of *two electric fluids,* and to speak rather of *two opposite electricities.* They may be distinguished indifferently by the names *vitreous* and *resinous,* or *positive* and *negative.*

The *one-fluid theory,* as originally propounded by Franklin, maintained the existence of only one electric fluid, which unelectrified bodies possess in a certain normal amount. A positively electrified body has more, and a negatively electrified body less than its normal amount. The particles of this fluid repel one another, and attract the particles of other kinds of matter, at all distances. Æpinus, in developing this theory more accurately, found it necessary to introduce the additional hypothesis that the particles of matter repel one another. Thus, according to Æpinus, the absence of sensible force between two bodies in the neutral condition, is due to the equilibrium of four forces, two of which are attractive, and the other two repulsive. Calling the two bodies A and B, the electricity which A possesses in normal amount, is repelled by the electricity of B, and attracted by the matter of B. The matter of A is attracted by the electricity of B, and repelled by the matter of B. These four forces are all equal, and destroy one another; but, without the supplementary hypothesis of Æpinus, one of the four forces is wanting, and the equilibrium is not easily explained. To reconcile Æpinus's addition with the Newtonian theory of gravitation, it is necessary to suppose that the equality between the four forces is not exact, the attractions being greater by an infinitesimal amount than the repulsions.

The one-fluid theory in this form is, like the two-fluid theory, consistent with the explanation of all known phenomena. But it is to be remarked that there is no sufficient reason, except established usage, for deciding which of the two opposite electricities should be regarded as corresponding to an excess of the electric fluid.

Franklin was the author of the terms positive and negative to denote the two opposite kinds of electrification; but the names can legitimately be retained without accepting the one-fluid theory, understanding that opposite signs imply forces in opposite directions, and that the connection between the *positive* sign and the forces exhibited by *vitreous* electricity is merely conventional.

562.—In speaking of electric currents, the language of the one-fluid theory is almost invariably employed. Thus, if A is a conductor charged positively, and B a conductor charged negatively; when the two are put in connection by a wire, we say that the direction of the current is from A to B; whereas the language of the two-fluid theory would be, that a current of vitreous or positive electricity travels from A to B, and a current of resinous or negative from B to A.

CHAPTER XLII.

ELECTRICAL INDUCTION.

563. Induction.—In the preceding chapter we have spoken of movements of material bodies caused by electrical attractions and repulsions. We have now to treat of the movement of electricity itself in obedience to the attractions or repulsions exerted upon it by other electricity. This kind of action is called *induction*.

It may be illustrated by means of the arrangement shown in Fig. 335. The apparatus consists of a sphere C which is electrified positively, suppose, and of a conducting insulated cylinder A B placed near it. From this latter are suspended at equal distances a few pairs of pith-balls. When the cylinder is brought near the sphere, the balls are observed to diverge. The divergence of the different pairs is not the same, but goes on decreasing from the pair nearest the cylinder until a point M is reached, where there is no divergence. Beyond this the divergence goes on increasing. The neutral point M does not exactly bisect the length of the cylinder, but is nearer the end A than the end B, and the former end is found to be more strongly electrified than the latter.

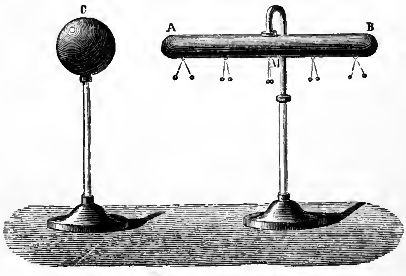


Fig. 335.—Electrification by Influence.

It is easy to show that the two ends of the cylinder are charged with opposite kinds of electricity; the end A being negatively, and

the end B positively electrified. We have only to bring an electrified stick of resin near the pith-balls at A, when these will be found to be repelled; if, on the contrary, it be held near those at B, they will be attracted.

The explanation is, that the positive electricity with which C is charged attracts the negative electricity of AB to the end A, and repels the positive to the end B. This action is more powerful at A than at B, on account of the greater proximity of the influencing body, and for the same reason the effect falls off more rapidly in the portion AM than in MB.

If the cylinder be brought closer to the sphere, the divergence of the balls increases; if it be removed farther from it, the divergence diminishes. Finally, all signs of electricity disappear if the sphere be taken away, or connected with the earth.

If, while the cylinder is under the influence of the electricity of C, the end B is connected with the earth, the pith-balls at this end

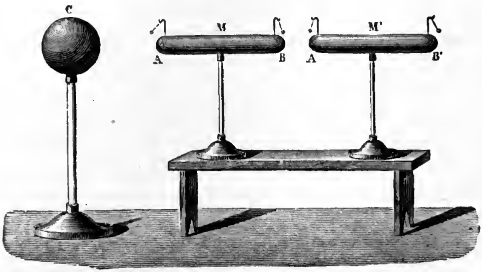


Fig. 336.—Successive Induction.

immediately collapse, while the divergence of those at A increases. The explanation is that the electricity which was repelled to the end B escapes to the earth, and thus affords an opportunity for a fresh exercise of induction on the part of the sphere, which increases the accumulation of negative electricity at A. We may also remark that the whole of the cylinder is now negatively electrified, the neutral line being pushed back to the earth. If the earth-connection be now broken, and the sphere C be then removed, the cylinder will remain negatively electrified, and will be in the same condition as if it had been touched by a negatively-electrified body. This mode

of giving a charge to a conductor is called *charging by induction*, and the charge thus given is always opposite to that of the *inducing body* C.

If a series of such conductors as A B be placed in line, without contact, and the positively-electrified body C be placed opposite to one end of the series, all the conductors will be affected in the same manner as the single conductor in the last experiment. They will all be charged with negative electricity at the end next C, and with positive electricity at the remote end, the effect, however, becoming feebler as we advance in the series. In this experiment each of the conductors acts inductively upon those next it; for example, if there be two conductors A B, A′B′, as in Fig. 336, the development of electricity at A′ and B′ is mainly due to the action of the positive electricity in MB. If the conductor AB be removed, the pith-balls at A′ and B′ will diminish their divergence.

The molecules of a body may be regarded as such a series of conductors, or rather as a number of such series. When an electrified body is brought near it, each molecule may thus become positive on one side and negative on the other. In the case of good conductors, this polarization is only instantaneous, being destroyed by the discharge of electricity from particle to particle. Good insulators are substances which are able to resist this tendency to discharge, and to maintain a high degree of polarization for a great length of time. This is Faraday's theory of "induction by contiguous particles."

564. Electrical Attraction and Repulsion.—The attraction which is observed when an electrified is brought near to an unelectrified body, is dependent upon induction. Suppose, for instance, that a body C, which is positively electrified, is brought near to an insulated and uncharged pith-ball. Negative electricity is induced on the near side of the pith-ball, and an equal quantity of positive on the further side. The former, being nearer to the body C, is more strongly attracted than the other is repelled. The ball is therefore upon the whole attracted.

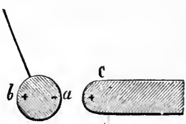


Fig. 337.—Electrical Attraction.

If the pith-ball, instead of being insulated, is suspended by a conducting thread from a support connected with the earth, it will be more strongly attracted than before, as it is now entirely charged with negative electricity.

In the case of any insulated conductor, the algebraic sum of the

electricities induced upon it by the presence of a neighbouring electrified body must be zero. If the pith-ball be insulated, and have an independent charge of either kind of electricity, the total force exerted on the pith-ball is the algebraic sum[1] of the two following quantities:—

(1) The force which the ball would experience, if it had no independent charge. This force, as we have just seen, is always attractive.

(2) The force due to the independent charge when distributed over the ball as it would be if C were removed. This second force is attractive or repulsive, according as the independent charge is of unlike or like sign to that of C. In the latter case, repulsion will generally be observed at distances exceeding a certain limit and attraction at nearer distances, the reason being that the force (1) due to the induced distribution increases more rapidly than the other as the distance is diminished.

It is important to remember this in testing, by the electric pendulum, or by any other electroscope, the kind of electricity with which a body is charged. In bringing the body towards the electroscope, the first movement produced is that which is to be observed, and repulsion is in general a more reliable test of kind of electricity than attraction.

565. Electroscopes.—An electroscope is an apparatus for detecting the presence of electricity, and determining its sign. The insulated electric pendulum is an electroscope. If the pith-ball, when itself uncharged, is attracted by a body brought near it, we know that the body is electrified. To determine the kind of electricity, the body is allowed to touch the pith-ball, which is then repelled. At this moment an excited glass tube is brought near. If it repels the ball, this latter, as well as the body which touched it, must be electrified positively. If the glass tube attracts it, or, still more decisively, if excited resin or sealing-wax repels it, the ball and the body which touched it are electrified negatively. The loss of electricity from the pith-ball is often so rapid as to render this test of sign somewhat uncertain.

The *gold-leaf electroscope* (Fig. 338) is constructed as follows:—

[1] We here suppose C to be a non-conductor, so that the distribution of its electricity is not affected by the presence of the pith-ball. If C be a conductor, the effect of induction upon it will be to favour attraction, so that an attractive force must be added to the two forces specified in the text.

Two small gold-leaves are attached to the lower end of a metallic rod, which passes through an opening in the top of a bell-glass, and terminates in a ball. The metallic rod is sometimes, for the sake of better insulation, inclosed in a glass tube secured by sealing-wax or some other non-conducting cement, and, for the same purpose, the upper part of the bell-glass is often varnished with shellac, which is less apt than glass to acquire a deposit of moisture from the air. The bell-glass is attached below to a metallic base, which excludes the external air. For the gold-leaves are sometimes substituted two straws, or two pith-balls suspended by linen threads; we have thus the *straw-electroscope* and the *pith-ball electroscope.*

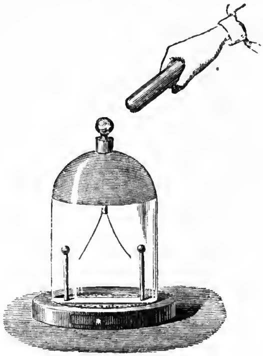


Fig. 333.—Gold-leaf Electroscope

To test whether a body is electrified, it is brought near the ball at the top of the electroscope. The like electricity is repelled into the leaves, and makes them diverge, while the unlike is attracted into the ball. The sign of the body's charge may be determined in the following manner:—While the leaves are divergent under the influence of the body, the operator touches the ball with his finger. This causes the leaves to collapse, and gives to the insulated conductor composed of leaves, rod, and ball, a charge opposite to that of the influencing body. The finger must be removed while the influencing body remains in position, as the amount of the induced charge depends upon the position of the influencing body at the instant of breaking connection. On now withdrawing the influencing body, the charge of unlike electricity is no longer attracted to the ball, but spreads over the whole of the conductor, and causes the leaves to diverge. If, while this divergence continues, an excited glass tube, when gradually brought towards the ball, diminishes the divergence, we know that the body in question was electrified positively. If it increases the divergence, the body was electrified negatively.

Great caution must be used in bringing electrified bodies near the gold-leaf electroscope, as the leaves are very apt to be ruptured by

quick movements. If they diverge so widely as to touch the sides of the bell-glass, it is often difficult to detach them from the glass without tearing. To prevent this contact, two metallic columns are interposed, communicating with the ground. If the leaves diverge too widely, they touch these columns and lose their electricity.

CHAPTER XLIII.

MEASUREMENT OF ELECTRICAL FORCES.

566. Coulomb's Torsion-balance.—Coulomb, who was the first to make electricity an accurate science, employed in his researches an instrument which is often called after his name, and which is still extensively employed. It depends on the principle that the torsion of a wire is simply proportional to the twisting couple. We shall first describe it, and then point out some of its applications.

It consists of a cylindrical glass case AA (Fig. 339), from the upper end B of which rises another glass cylinder DD of much smaller diameter. This small cylinder is fitted at the top with a brass cap *a*, carrying an index C. Outside of this, and capable of turning round it, is another cap *b*, the top of which is divided into 360 equal parts. In the centre of the cap *b* is an opening through which passes a small metal cylinder *d*, capable of turning in the opening with moderate friction, and having at its lower end a notch or slit. When the cap *b* is turned, the cylinder *d* turns with it; but the latter can also be turned separately, so as not to change the reading. These parts compose the *torsion-head*. A very fine metallic wire is held by the notch, and supports a small piece of metal, through which passes a light needle of shellac *f*, carrying at one end a small gilt ball *g*. A circular

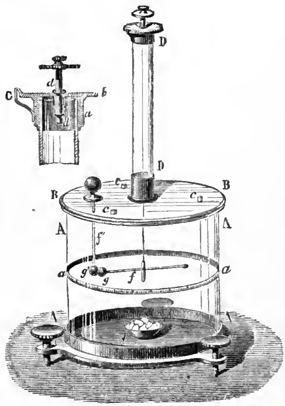


Fig. 339.—Coulomb's Torsion-balance.

scale runs round the outside of the large cylinder in the plane of the needle. Finally, opposite the zero of this scale, there is a fixed ball g' of some conducting material, supported by a rod f' of shellac, which passes through a hole in the cover of the cylindrical case.

567. Laws of Electric Repulsion.—To illustrate the mode of employing this apparatus for electrical measurements, we shall explain the course followed by Coulomb in investigating the law according to which electrical repulsions and attractions vary with the distance. The index is set to the zero of the scale. The inner cylinder d is then turned, until the movable ball just touches the fixed ball without any torsion of the wire. The fixed ball is then taken out, placed in communication with an electrified body, and replaced in the apparatus. The electricity with which it is charged is communicated to the movable ball, and causes the repulsion of this latter through a number of degrees indicated by the scale which surrounds the case. In this position the force of repulsion is in equilibrium with the force of torsion tending to bring back the ball to its original position. The graduated cap b is then turned so as to oppose the repulsion. The movable ball is thus brought nearer to the fixed ball, and at the same time the amount of torsion in the wire is increased. By repeating this process, we obtain a number of different positions in which repulsion is balanced by torsion. But we know, from the laws of elasticity, that the force (strictly the couple[1]) of torsion is proportional to the angle of torsion. Hence we have only to compare the total amounts of torsion with the distances of the two balls. By such comparisons Coulomb found that the force of electrical repulsion varies *inversely as the square of the distance.*

The following are the actual numbers obtained in one of the experiments. The original deviation of the movable ball being 36°, it was found that, in order to reduce this distance to 18°, it was necessary to turn the head through 126°, and, for a farther reduction of the deviation to 8°·5, an additional rotation through 441° was required. It will thus be perceived that at the distances of 36°, 18°, and 8°·5, which may be practically considered as in the ratio of 1, $\frac{1}{2}$, and $\frac{1}{4}$, the forces of repulsion were equilibrated by torsions of 36°,

[1] The repulsive force on the movable ball is equivalent to an equal and parallel force acting at the centre of the needle (the point of attachment of the wire), and a couple whose arm is the perpendicular from this centre on the line joining the balls. This couple must be equal to the couple of torsion. The other component produces a small deviation of the suspending wire from the vertical.

$126^\circ+18^\circ=144^\circ$, and $441+126+8{\cdot}5=575^\circ{\cdot}5$ respectively. Now 144 is 36×4, and $575{\cdot}5$ may be considered as 576, or 36×16. Hence we perceive that, as the distance is divided by 2, or by 4, the force of repulsion is multiplied by 4 or by 16, which precisely agrees with the law enunciated above.

568. Equation of Equilibrium.—We must, however, observe that in this mode of reducing the observations two inaccurate assumptions are made. First, the distance between the balls is regarded as being equal to the arc which lies between them, whereas it is really the chord of that arc. Secondly, the force of repulsion is regarded as acting always at the same arm, whereas its arm, being the perpendicular from the centre on the chord, diminishes as the distance increases. The following investigation is more rigorous.

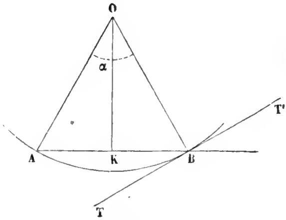


Fig. 340.

Let AOB (Fig. 340), the angular distance of the balls, be denoted by α, and let l be the length of the radius OA. Then the chord AB is $2l \sin \frac{1}{2}\alpha$, and the arm OK is $l \cos \frac{1}{2}\alpha$. Let f denote the force of repulsion at unit distance, and n the couple of torsion for 1°. Then the force of repulsion in the given position is $\frac{f}{4\,l^2 \sin^2 \frac{1}{2}\alpha}$ if the law of inverse squares be true, and the moment of this about the centre is $\frac{f \cos \frac{1}{2}\alpha}{4\,l \sin^2 \frac{1}{2}\alpha}$, which must be equal to nA, if A be the number of degrees of torsion. Hence we have

$$\frac{f}{4\,n\,l} = \mathrm{A} \sin \tfrac{1}{2}\alpha \tan \tfrac{1}{2}\alpha,$$

and as the first member of this equation is constant, the second member must be constant also for different values of A and α, if the law of inverse squares be true. The degree of constancy is shown by the following table:—

	α	A	A $\sin \frac{1}{2}\alpha \tan \frac{1}{2}\alpha$.
1st experiment, ...	36	36	3·614
2d experiment, ...	18	144	3·568
3d experiment, ...	8·5	575·5	3·169
Supposed case, ...	9	576	3·557

The difference between the first and second numbers of the last

column is insignificant. That between the second and third is more considerable,[1] but in reality only corresponds to an error of half a degree in the measurement of the arc.

569. Case of Attraction.—The law of attractions may be investigated by a similar method. The index is set to zero, and the central piece is turned so as to place the movable ball at a known distance from the fixed ball. The two balls are then charged with electricity of different kinds. The movable ball is accordingly attracted towards the other, and settles in a position in which attraction is balanced by torsion. By altering the amount of torsion, different positions of the ball can be obtained. On comparing the distances with the corresponding torsions, it is found that the same law holds as in the case of repulsion. The experiment, however, is difficult, and is only possible when the balls are very feebly electrified. To prevent the contact of the two balls, Coulomb fixed a silk thread in the instrument, so as to stop the course of the movable ball.

570. Law of Attraction and Repulsion as depending on Amount of Charge.—We may assume as evident, that when an electrified ball is placed in contact with a precisely equal and similar ball, the charge will be divided equally between them, so that the first will retain only half the charge which it had before contact.

Suppose that an observation on repulsion has just been made with the torsion-balance, and that we touch the fixed ball with another exactly equal insulated ball, which we then remove. It will be found that the amount of torsion requisite for keeping the movable ball in its observed position is just half what it was before. The

[1] We have already seen that the mutual induction of two conductors tends to diminish their mutual repulsion, and that this inductive action becomes more important as the distance is diminished. Hence the repulsion at distance 9 should be less than a quarter of that at distance 18. The apparent error thus confirms the law.

Many persons have adduced, as tending to overthrow Coulomb's law of inverse squares, experimental results which really confirm it. Except when the dimensions of the charged bodies are very small in comparison with the distance, the observed attraction or repulsion is the resultant of an infinite number of forces acting along lines drawn from the different points of the one body to the different points of the other. The law of inverse squares applies directly to these several components, and not to the resultant which they yield. The latter can only be computed by elaborate mathematical processes.

It is incorrectly assumed in the text that the law ought to apply directly to two spheres, when by their distance we understand the distance between their nearest points. It is not obvious that the distance of the nearest points should give a better result than the distance between the centres.

The strongest evidence for the rigorous exactness of the law of inverse squares is indirect; see § 574.

same result will be obtained by touching the movable ball with a ball of its own size. We conclude that, if the charge of either body be altered, the attractive or repulsive force between the bodies at given distance will be altered in the same ratio. The law is not rigorously true for bodies of finite size, unless the distribution of the electricity on the two bodies remains unchanged. When the two bodies are very small in all their dimensions in comparison with the distance between them, their mutual force is represented by the expression

$$\frac{q q'}{D^2},$$

q and q' denoting their charges, and D the distance. If this expression has the positive sign, the force is repulsive, if negative attractive.

571. Electricity resides on the Surface.—Electricity (subject to the

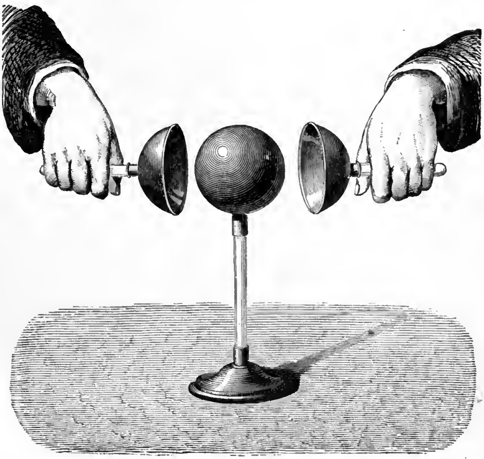


Fig. 341.—Biot's Experiment.

exceptions mentioned below) resides exclusively on the external surface of a conductor. This is perhaps implied in the experimental fact frequently observed by Coulomb, that when a solid and a hollow sphere of equal external diameter are allowed to touch each other, any charge possessed by either is divided equally between them. A

direct demonstration is afforded by the following experiment of Biot:—

We take an insulated sphere of metal, charge it with electricity, and cover it with two hemispheres furnished with insulating handles, which fit the sphere exactly (Fig. 341). If the two hemispheres be quickly removed, and presented to an electric pendulum, they will be found to be electrified, while the sphere itself will show hardly any traces of electricity. We must, however, remark that this experiment is rarely successful, and that generally the sphere remains very sensibly electrified. The reason of this is, that it is very difficult to remove the hemispheres so steadily, as not to permit their edges to touch the sphere after the first separation.

The following is a much surer form of the experiment:—

A hollow insulated sphere, with an orifice in the top, is charged with electricity (Fig. 342). A *proof-plane*, consisting of a small disc of gilt paper insulated by a thin handle of shellac, is then applied to the interior surface of the sphere, and, when tested by an electric pendulum or an electroscope, is found to exhibit no trace of electricity. But if, on the contrary, the disc be applied to the external surface of the sphere, it will be found to be electrified, and capable of attracting light bodies. Faraday varied this experiment, by substituting a cylinder of wire-gauze for the sphere. This cylinder rested on an insulated disc of metal. The disc was charged with electricity, and it was found that no trace of the electricity could be detected by applying the proof-plane to the interior surface of the cylinder.

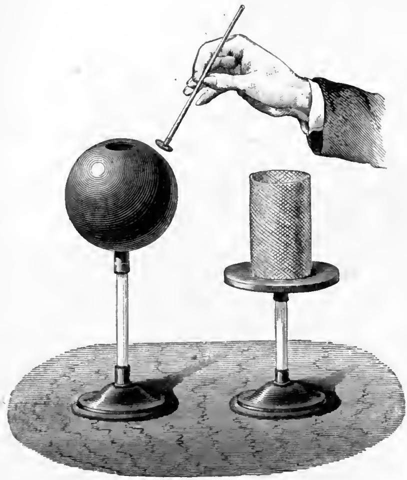


Fig. 342.—Proof-plane and Hollow Sphere.

The following experiment is also due to Faraday. A metal ring is fixed upon an insulating stand (Fig. 343). To this ring is attached a cone-shaped bag of fine linen, which is a conductor of electricity. A silk thread, attached to the apex of the cone, and extending both

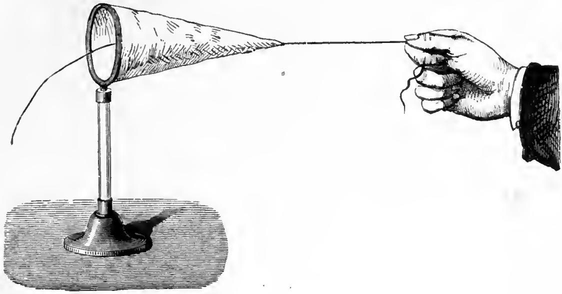


Fig. 343.—Faraday's Experiment.

ways, enables the operator to turn the bag inside out as often as required, without discharging it. When the bag is electrified, the application of the proof-plane always shows that there is electricity on the outer, but not on the inner surface. When the bag is turned inside out, the electricity therefore passes from one surface of the linen to the other.

572. Limitations of the Rule.—There are two exceptions to the rule that electricity is confined to the external surface of a conductor.

1. It does not hold for electric currents. We shall see hereafter in connection with galvanic electricity, that the resistance which a wire of given length opposes to the passage of electricity through it, depends not upon its circumference but upon its sectional area. A hollow wire will not conduct electricity so well as a solid wire of the same external diameter.

2. Electricity may be induced on the inner surface of a hollow conductor by the presence of an electrified body insulated from the conductor itself. If an insulated body charged with electricity be introduced into the interior of a hollow conductor, so as to be completely surrounded by it, but still insulated from it, it induces upon the inner surface a quantity equal to its own charge, but of opposite sign. If the conductor is insulated, an equal quantity, but of the same sign as the charge of the inclosed body, is repelled to the outside, and

this is true whether the conductor has an independent charge of its own or not. In this case, then, we have electricity residing on both the external and the internal surfaces of a hollow conductor, but it still resides only on the surfaces.

If a conducting body connected with the earth be introduced into the interior of a hollow charged conductor, so as to be partially surrounded by it, the body thus introduced will acquire an opposite charge by induction, and, by the reciprocal action of this charge, electricity will be induced on the inner at the expense of the outer surface of the hollow conductor, just as in the preceding case.

573. Ice-pail Experiment.—The effect of introducing a charged body within a hollow conductor is well illustrated by the following experiments of Faraday. Let A (Fig. 344) represent an insulated pewter ice-pail, ten and a half inches high and seven inches in diameter, connected by a wire with a delicate gold-leaf electroscope E, and let C be a round brass ball insulated by a dry thread of white silk, three or four feet in length, so as to remove the influence of the hand holding it from the ice-pail below. Let A be perfectly discharged, and let C, after being charged at a distance, be introduced into A as in the figure. If C be positive, E also will diverge positively; if C be taken away, E will collapse perfectly, the apparatus being in good order. As C enters the vessel A, the divergence of E will increase until C is about three inches below the edge of the vessel, and will remain quite steady and unchanged for any greater depression. If C be made to touch the bottom of A, all its charge is communicated to A, and C, upon being withdrawn and examined, is found perfectly discharged. Now Faraday found that at the moment of contact of C with the bottom of A, not the slightest change took place in the divergence of the gold-leaves. Hence the charge previously developed by induction on the outside of A must have been precisely equal to that acquired by the contact, that is, must have been equal to the charge of C.

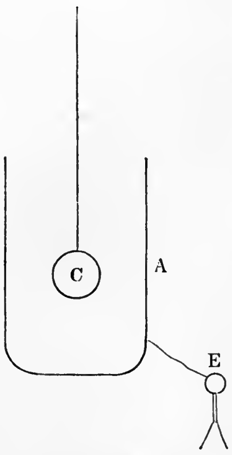


Fig. 344.—Ice-pail Experiment.

He then employed four ice-pails (Fig. 345), arranged one within the other, the smallest innermost, insulated from each other by plates of shellac at the bottom, the outermost pail being connected with the electroscope. When the charged carrier-ball C was introduced within the innermost pail, and lowered until it touched the bottom, the electrometer gave precisely the same indications as when the outermost pail was employed alone. When the innermost was lifted out by a silk thread after being touched by C, the gold-leaves collapsed perfectly. When it was introduced again, they opened out to the same extent as before. When 4 and 3 were connected by a wire let down between them by a silk thread, the leaves remained unchanged, and so they still remained when 3 and 2 were connected, and finally when all four pails were connected.

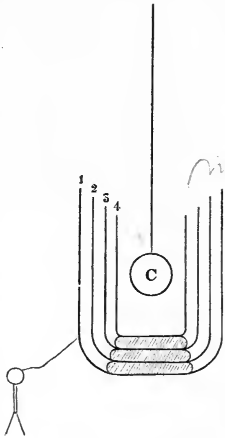


Fig. 345.—Experiment with Four Ice-pails.

574. No Force within a Conductor.—When a hollow conductor is electrified, however strongly, no effect is produced upon pith-balls, gold-leaves, or any other electroscopic apparatus in the interior, whether connected with the hollow conductor, or insulated from it, provided, in the latter case, that they have no communication with bodies external to the hollow conductor. Faraday constructed a cubical box, measuring 12 feet each way, covered externally with copper wire and tin-foil, and insulated from the earth. He charged this box very strongly by outside communication with a powerful electrical machine; but a gold-leaf electrometer within showed no effect. He says, "I went into the cube and lived in it, using lighted candles, electrometers, and all other tests of electrical states. I could not find the least influence upon them, or indication of anything particular given by them, though all the time the outside of the cube was powerfully charged, and large sparks and brushes were darting off from every part of its outer surface."

The fact that electricity resides only on the external surface of a conductor, combined with the fact that there is no electrical force in the space inclosed by this surface, affords a rigorous proof of the law

of inverse squares. For if the conductor be a sphere removed from the influence of external bodies, its charge must be distributed uniformly over its surface. Now it admits of proof, and is well known to mathematicians, that a uniform spherical shell exerts no attraction at any point of the interior space, if the law of attraction be that of inverse squares, and that the internal attraction does not vanish for any other law.

575. Electrical Density and Distribution.—When the proof-plane is applied to different parts of the surface of a conductor, the quantities of electricity which it carries off are not usually equal. But the electricity carried off by the proof-plane is simply the electricity which resided on the part of the surface covered by it, for the proof-plane during the time of its contact is virtually part of the surface of the conductor. We must therefore conclude that equal areas on different parts of the surface of a conductor have not equal amounts of electricity upon them. It is also found that if the charge of the conductor be varied, the electricity resident upon any specified portion of the surface is changed in the same ratio. The ratio of the quantities of electricity on two specified portions of the surface is in fact independent of the charge, and depends only on the form of the conductor. This is expressed by saying that *distribution* is independent of charge, and that the distribution of electricity on the surface of a conductor depends on its form.

By the *average electrical density* on the whole or any specified portion of the surface of a conductor, is meant the quantity of electricity upon it, divided by its area. By the *electrical density at a specified point* on the surface of a conductor, is meant the average electrical density on an exceedingly small area surrounding it, in other words, the *quantity of electricity per unit area* at the point. The name is appropriate, from the analogy of ordinary material density, which is mass per unit volume, and is not intended to imply any hypothesis as to the nature of electricity. The name was introduced by Coulomb, who first investigated the subject in question, and is generally employed by the best electricians in this country. The term *thickness of electrical stratum*, which was introduced by Poisson, is much used in France, but is more open to objection from the coarse assumptions which it seems to involve.

The following are some of Coulomb's results. The dotted line in each of the figures is intended to represent, by its distance from the outline of the conductor, the electric density at each point of the

latter. In all cases it is to be understood that the conductor is so far removed from external bodies as not to be influenced by them:—

1. *Sphere* (Fig. 346). The electric density is the same for all points on the surface of a spherical conductor.

2. *Ellipsoid* (Fig. 347). The density is greatest at the ends of the

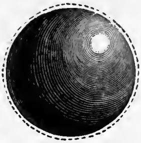


Fig. 346.—Distribution on Sphere.

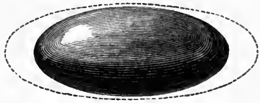


Fig. 347.—Distribution on Ellipsoid.

longest, and least at the ends of the shortest axis; and the densities at these points are simply proportional to the axes themselves.[1]

3. *Flat Disc* (Fig. 348). The density is almost inappreciable over the whole of both faces, except close to the edges, where it increases almost *per saltum*.

4. *Cylinder with Hemispherical Ends* (Fig. 349). The density is

Fig. 348.—Distribution on Disc.

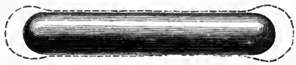


Fig. 349.—Distribution on Cylinder with rounded ends.

a minimum, and nearly uniform, at parts remote from the ends, and attains a maximum at the ends. The ratio of the density at the ends to that at the sides increases as the radius of the cylinder diminishes, the length of the cylinder remaining the same.

5. *Spheres in Contact.*—In the case of equal spheres, the charge, which is nothing at the point of contact, and very feeble up to 30° from that point, increases very rapidly from 30° to 60°, less rapidly from 60° to 90°, and almost insensibly from 90° to 180°. When the spheres are of unequal size, the charge at any point on the smaller

[1] More generally, the density at any point on the surface of an ellipsoid is proportional to the length of a perpendicular from the centre of the ellipsoid on a tangent plane at the point.

If an ellipsoid, similar and nearly equal to the given one, be placed so that the corresponding axes of the two are coincident, we shall have a thin ellipsoidal shell, whose thickness at any point exactly represents the electric density at that point.

Such a shell, if composed of homogeneous matter attracting inversely as the square of the distance, would exercise no force at points in its interior.

sphere is greater than at the corresponding point on the larger one; and as the smaller sphere is continually diminished, the other remaining the same, the ratio of the densities at the extremities of the line of centres tends to become 2 : 1.

576. Method of Experiment.—The preceding results were obtained by Coulomb in the following manner. He touched the electrified body at a known point with the proof-plane, and then put the plane in the place of the fixed ball of the torsion-balance, the movable ball having previously been charged with electricity of the same sign. Repulsion was thus produced, and the amount of torsion necessary to keep the balls at a certain distance asunder was observed. He then repeated the experiment with electricity taken from a different point of the body under examination, and the ratio of the densities at the two points was given by the ratio of the torsions necessary to keep the balls at the same distance.

By way of checking the accuracy of this mode of experimentation, Coulomb electrified an insulated sphere, and measured the electric density on its surface by the method described above. He then touched the sphere with another precisely equal sphere, and on again applying the proof-plane he found that the charge carried off by the plane was just half what it had been before.

577. Alternate Contact.—The above experiments naturally require some time, during which the body under investigation is gradually losing its charge. The consequence is, that the densities indicated by the balance, if taken singly, do not correctly represent the electric distribution. This source of error was avoided by Coulomb in the following manner. He touched two points on the body successively, and determined the electric density at each; and then, after an interval equal to that between the two experiments, he touched the first point again, and obtained a second measure of its density, which was less than the first, on account of the dissipation of electricity. If the densities thus observed be denoted by A and A′, and the density observed at the second point by B, it is evident that $\frac{A}{B}$ is greater, and $\frac{A'}{B}$ less than the ratio required. Coulomb adopted, as the correct value, their arithmetic mean $\frac{1}{2}\,\frac{A+A'}{B}$.

578. Power of Points.—The distribution of electricity on a conductor of any form may be roughly described, by saying that the density is greatest on those parts of the surface which project most,

or which have the sharpest convexity, and that in depressions or concavities it is small or altogether insensible. Theory shows that at a perfectly sharp edge, such, for example, as is formed by two planes meeting at any angle however obtuse, but *not rounded off*, the density must be infinite, and *a fortiori* it must be infinite at a perfectly sharp point, for example at the apex of a cone, however obtuse, *if not rounded off*. Practically, the points and edges of bodies are always rounded off; the microscope shows them merely as places of very sharp convexity (that is, of very small radius of curvature), and hence the electric density at those places is really finite; but it is exceedingly great in comparison with the density at other parts, and this is especially true of very acute points, such as the point of a fine needle. The consequence is, that if a pointed conductor is insulated and charged, the concentration of a large amount of repulsive force within an exceedingly small area produces very rapid escape of electricity at the points. Conductors intended to retain a charge of electricity must have no points or edges, and must be very smooth. If of considerable length in proportion to their breadth, they are usually made to terminate in large knobs.

579. Dissipation of Charge.—When an insulated conductor is charged and left to itself, its charge is gradually dissipated, and at length completely disappears. This loss takes place partly through the supports, and partly through the air.

As regards the supports, the loss occurs chiefly at their surface, especially if (as is usually the case) they are not perfectly dry. It is diminished by diminishing their perimeter, and by increasing their length; for example, a long fibre of glass or raw silk is an excellent insulator.

As regards the air, we must distinguish between conduction and convection. Very hot air and highly rarefied air probably act as conductors; but air in the ordinary condition acts chiefly by contact and convection. Successive layers of air become electrified by contact with the conductor, and are then repelled, carrying off the electricity which they have acquired. It is by an action of this kind that electricity escapes into the air from points, as is proved by the wind which passes off from them (§ 598). Particles of dust present in the air, in like manner, act as carriers, being attracted to the conductor, charged by contact with it, and then repelled. They also frequently adhere by one end to the conductor,

and thus constitute pointed projections through which electricity is discharged into the air.

Coulomb deduced from his observations on dissipation of charge a law precisely analogous to Newton's law of cooling, namely, that when all other circumstances remain the same, *the rate of loss is simply proportional to the charge,* so that the charges at equal intervals of time form a decreasing geometric series. Subsequent experience has confirmed this law, as approximately true for moderate charges of the same sign. Negative charges are, however, dissipated more rapidly than positive.

repulsion = positive } called
attraction = neg } so in Physics.

CHAPTER XLIV.

ELECTRICAL MACHINES.

580. Electrical Machines.—The first electrical machine was invented by Otto Guericke, to whom, as we have already seen (§ 229), science is indebted for the invention of the air-pump. It consisted of a ball of sulphur which was turned upon its axis by one person, while another held his hands upon the ball, thus causing the friction necessary for the production of electricity. The result was that the globe was negatively electrified, and the positive electricity escaped into the earth through the hands of the operator. This machine, however, was capable of producing only very feeble effects, and the sparks obtained from it were visible only in the dark. An English philosopher, Hawksbee, substituted a globe of glass for the globe of sulphur; the electricity thus obtained was positive, and the sparks obtained by the new machine were of considerable brightness. The machine, however, was for the time superseded by the use of glass tubes, which continued to be the favourite instruments for generating electricity until the middle of the eighteenth century, when a German philosopher, Boze, professor of physics at Wittemberg, revived and perfected Hawksbee's machine, which became universally adopted.

Fig. 350, which is taken from the *Leçons de Physique* of the Abbé Nollet, published in 1767, shows the arrangement of the machine adopted by this celebrated philosopher. It consists of a large wheel, round which is passed an endless cord, which, passing also round a pulley, serves to turn a glass globe when the wheel is set in motion. The electricity thus produced is collected on a conductor suspended from the ceiling by silk cords.

It will be observed that, in the figure, the friction is produced by the hand. This mode of applying friction, which is evidently rude

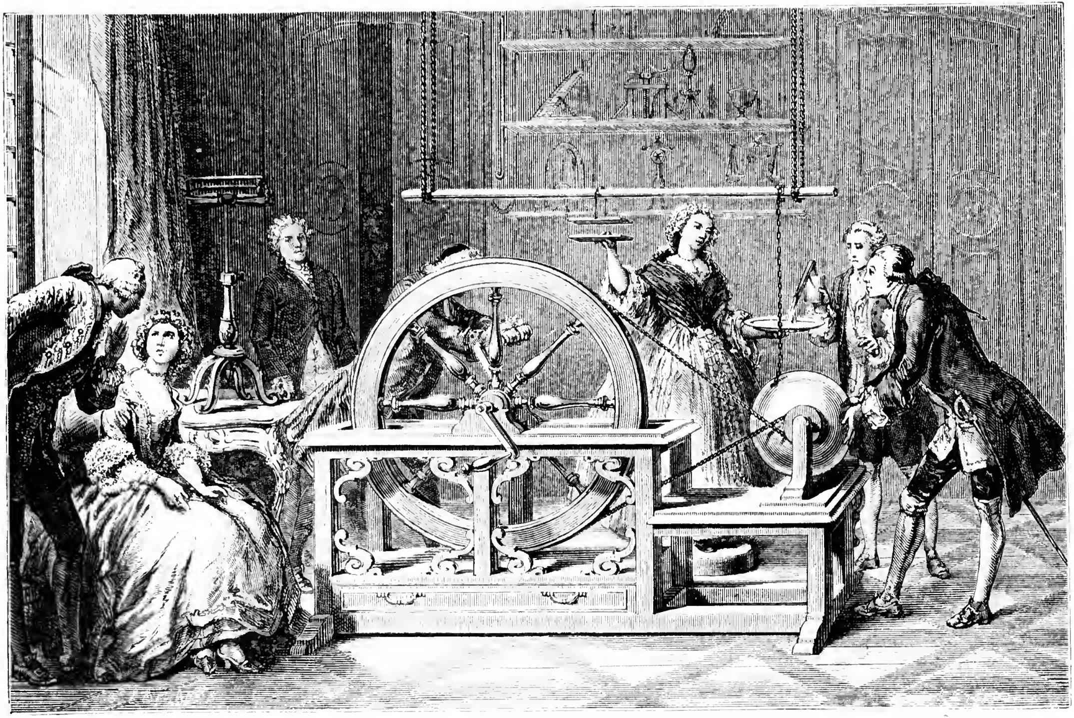


Fig. 350.—Hawksbee's Electrical Machine.

and defective, was nevertheless long used for want of a better, though many attempts were made to replace it by the use of rubbers of leather, stuffed with hair, and pressed against the globe by means of regulating screws. The shape of the globe rendered the use of these very difficult, and it was not until a cylinder was substituted for the globe that they were generally adopted.

581. Ramsden's Machine.—The kind of machine most commonly employed at present is the plate-machine, invented by Ramsden about 1768, and only slightly changed and improved since.

The most usual form of this machine is shown in Fig. 351. It

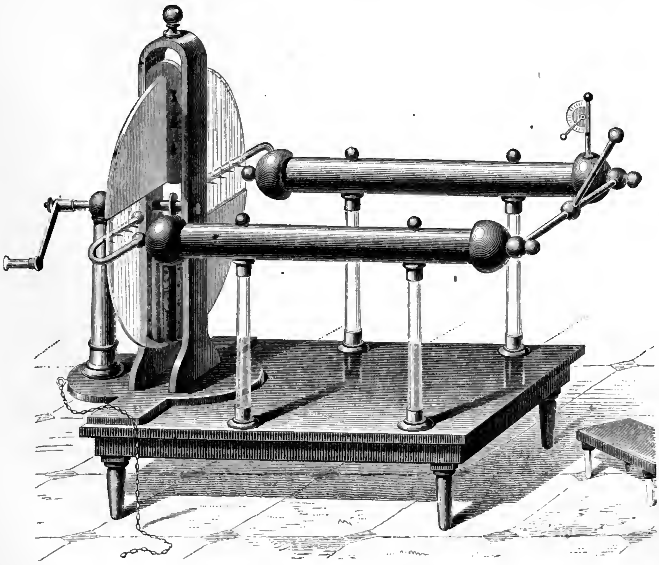


Fig. 351.—Ramsden's Electrical Machine.

has a circular plate of glass, which turns on an axis supported by two wooden uprights. On each side of the plate, at the upper and lower parts of the uprights, are two cushions, which act as rubbers when the plate is turned. In front of the plate are two metallic conductors supported on glass legs, and terminating in branches which are bent round the plate at the middle of its height, and are

studded with points projecting towards it. The plate becomes charged with positive electricity by friction against the cushions, and gives off its electricity through the points to the two conductors, or, what amounts to the same thing, the conductors give off negative electricity through the points to the positively-electrified plate. In order to avoid loss of electricity from that portion of the plate which is passing from the cushions to the points, sector-shaped pieces of oiled silk are placed so as to cover it on both sides. The cushions become negatively electrified by the friction; and the machine will not continue working unless this negative electricity is allowed to escape. The cushions are accordingly connected with the earth by means of metal plates let into their supports.

582. Limit of Charge.—As the conductors become more highly charged, they lose electricity to the air more rapidly, and a time soon arrives when they lose electricity as fast as they receive it from the plate. After this, if the machine continues to be worked uniformly, their charge remains nearly constant. This limiting amount of charge depends very much upon the condition of the air; and in damp weather the machine often refuses to work unless special means are employed to keep it dry.

The rubbers are covered with a metallic preparation, of which several different kinds are employed. Sometimes it is the compound called *aurum musivum* (bisulphide of tin), but more frequently an amalgam. Kienmeier's amalgam consists of one part of zinc, one of tin, and two of mercury. The amalgam is mixed with grease to make it adhere to the leather or silk which forms the face of the cushion.

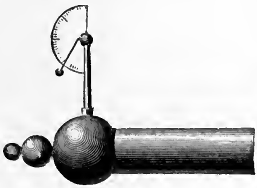


Fig. 352.—Quadrant Electroscope.

Before using the machine, the glass legs which support the conductors should be wiped with a warm dry cloth. The plate must also be cleaned from any dust or portions of amalgam which may adhere to it, and lastly, dried with a hot cloth or paper. When these precautions are taken the machine, if standing near a fire, will always work; but the charging of Leyden jars, and especially of batteries, may be rendered impossible by bad weather.

The variations of charge are indicated by the *quadrant electroscope* (Fig. 352), which is attached to one of the conductors. It consists

of an upright conducting stem, supporting a quadrant, or more commonly a semicircle, of ivory, at whose centre a light needle of ivory is jointed, carrying a pith-ball at its end. When there is no charge in the conductor, this pendulum hangs vertically, and as the charge increases it is repelled further and further from the stem. In damp weather it will be observed to return to the vertical position almost immediately on ceasing to turn the machine, while in very favourable circumstances its gives a sensible indication of charge after two or three minutes.

583. Nairne's Machine.—Ramsden's machine furnishes only positive electricity. In order to obtain negative electricity, it is necessary to

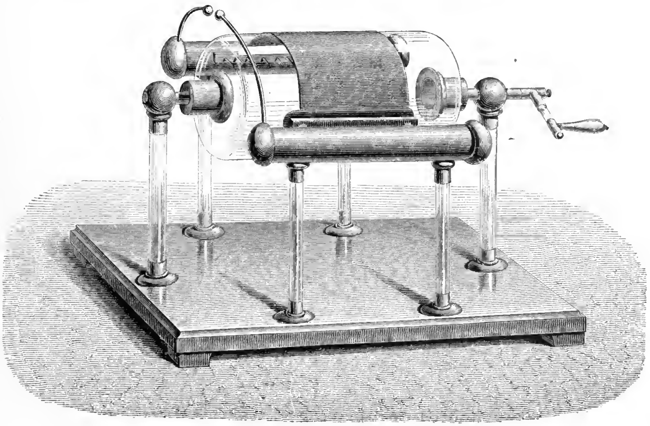


Fig. 353.—Nairne's Electrical Machine.

insulate the cushions from the ground, and to place them in communication with an insulated conductor. An arrangement of this kind is adopted in Nairne's machine.

In this machine a large cylinder of glass revolves between two separately insulated conductors. One of these has a row of points projecting towards the glass, and collects positive electricity. The other is connected with the rubber, and collects negative. If one kind of electricity only is required, the conductor which furnishes the other must be connected with the ground.

584. Winter's Machine.—Winter, of Vienna, has introduced some modifications in Ramsden's machine.

Instead of four cushions, there are, as will be seen by the figure (Fig. 354), only two, which are in communication with a spherical conductor, supported on a glass pillar. This may be used to collect negative electricity, in the same way as the negative conductor in Nairne's machine. The chief or positive conductor consists of an insulated sphere, on the top of which is often another sphere of smaller size. The positive electricity is collected from the plate by

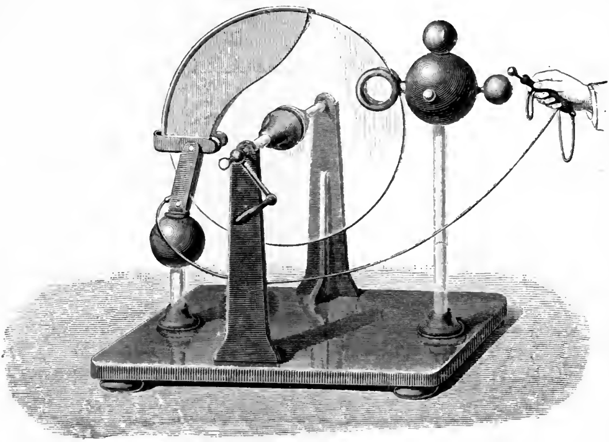


Fig. 354.—Winter's Electrical Machine.

means of two rings opposite to each other, one on each side of the plate. On the side next the plate, they have a groove, which is lined with metal, and studded with points. They are supported by an arm which is inserted in the positive conductor. The size of the positive conductor is often increased by the addition of a very large ring (3 or 4 feet in diameter) which is supported on the top of the large sphere. The ring consists of very stout brass wire inclosed in well-polished mahogany.

Winter's machine appears to give longer sparks than the ordinary machine under the same circumstances. This circumstance is owing, partly at least, to the considerable distance between the rubber and the positive conductor, which prevents the occurrence of discharges between them.

585. Hydro-electric Machine.—About the year 1840, Mr. (now Sir) W. Armstrong invented an electric machine, in which electricity was generated by the friction of steam against the sides of orifices, through which it is allowed to escape under high pressure. It consists of a

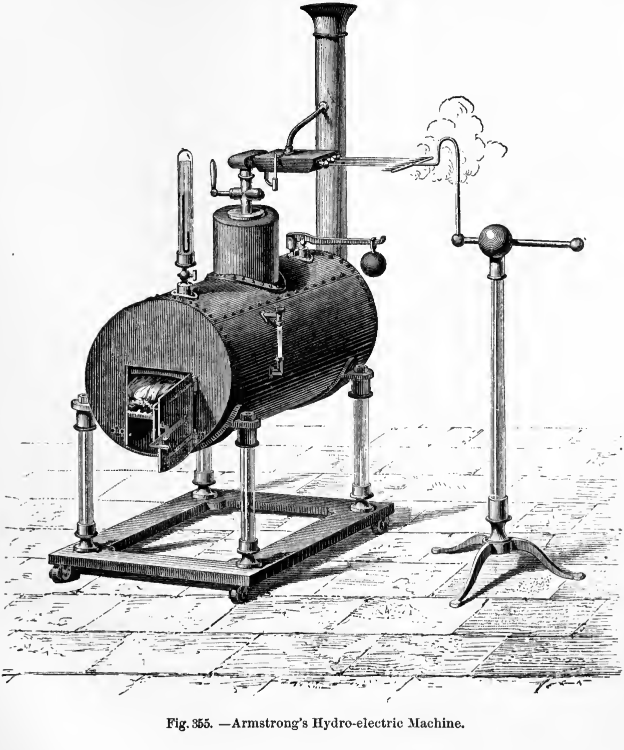


Fig. 355. —Armstrong's Hydro-electric Machine.

boiler with the fire inside, supported on four glass legs. The steam, before escaping, passes through a number of tubes which traverse a cooling-box containing water, into which dip meshes of cotton, which are led over the tubes, and passed round them. The cooling thus produced in the tubes, causes partial condensation of the steam. This has been found to be an indispensable condition, the friction of per-

fectly dry steam being quite inoperative. Speaking strictly, it is the friction of the drops of water against the sides of the orifice, which generates the electricity, and the steam merely furnishes the means of applying the friction. The jet of steam is positively, and the boiler negatively electrified. The positive electricity is collected by directing the jet of steam upon a metal comb communicating with an insulated conductor.

The form of the outlet by which the steam escapes is shown in Fig. 356. The steam is checked in its course by a tongue of metal, round which it has to pass, before it can enter the wooden tube through which it escapes into the air. This machine, in order to work well, requires a pressure of several atmospheres. The water in the boiler should be distilled water. If a saline solution be introduced into the tube through which the steam escapes, all traces of electricity immediately disappear. The generation of electricity varies, both in sign and degree, according to the substance of which the escape-tube is composed, and according to the liquid whose particles are carried out by the steam. Thus, when a small quantity of oil of turpentine is introduced into the jet of steam, the boiler becomes positively, and the steam negatively electrified.

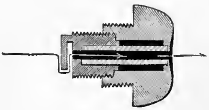


Fig. 356.—Outlet of Steam.

The hydro-electric machine is exceedingly powerful. At the Polytechnic Institution in London, there was one with a boiler 78 inches long and 42 in diameter, and with 46 jets. Sparks were obtained from the conductor at the distance of 22 inches. The machine is, however, very inconvenient to manage. A long time is required to get up the requisite pressure of steam. The boiler must be carefully washed with a solution of potash, after each occasion of its use; and, finally, the working of the machine is necessarily accompanied by the disengagement of an enormous quantity of steam, which, besides causing a deafening noise, has the mischievous effect of covering with moisture everything within reach. Accordingly, though very interesting in itself, it is by no means adapted to the general purposes of an electrical machine.

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586. Electrophorus.—When electricity is required in comparatively small quantities, it is readily supplied by the simple apparatus called the *electrophorus*. This consists (Fig. 357) of a disc of resin, or some other material easily excited by friction, and of a polished metal

disc B with an insulating handle C D. The resin disc is electrified by striking or rubbing it with catskin or flannel, and the metal plate is then laid upon it. In these circumstances the upper plate does not receive a direct charge from the lower, but, if touched with the finger (to connect it with the earth), receives an opposite charge by induction. On lifting it away by its insulating handle, it is found to be charged, and will give a spark. It may then be replaced on the lower plate (touching it at the same time with the finger), and the process repeated an indefinite number of times, without any fresh excitation, if the weather is favourable.

Fig. 357.—Electrophorus.

The resinous plate has usually a base or *sole* of metal, which is in connection with the earth while the electrophorus is being worked. When the cover receives its positive charge on being connected with the earth, the sole at the same time receives from the earth a negative charge, and as the cover is gradually lifted this negative charge gradually returns to the earth.

The most convenient form of the electrophorus is that of Professor Phillips, in which the cover, when placed upon the resinous plate, comes into metallic connection with the metal plate below. That this arrangement is allowable is evident, when we reflect that, when the upper plate is touched with the finger, it is in fact connected with the lower plate, since both are connected with the earth; and it effects a great saving of time when many sparks are required in quick succession, for the cover may be raised and lowered as fast as we please, coming alternately into contact with the resinous plate and the body which we wish to charge.

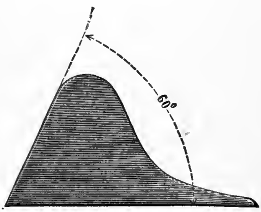

Fig. 358.—Electrified Sector.

587. Bertsch's Electrical Machine.— A machine which has been called a rotatory electrophorus was invented a few years ago by Bertsch, and is represented in Fig. 359. A circular plate of ebonite D can be made to revolve rapidly. A sector of the same material (Fig. 358), previously excited by friction, is

fixed opposite the lower portion of the plate; and on the other side, immediately opposite to this, is a metallic comb N forming the extremity of a conductor connected with the earth. At the upper part is another comb M connected with the conductor A. Under

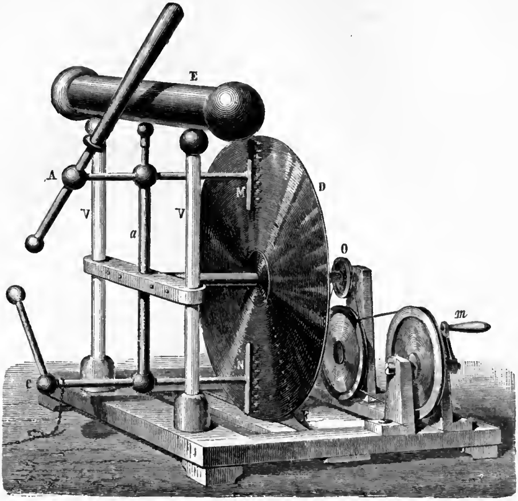

Fig. 359.—Bertsch's Electrical Machine.

the influence of the electrified sector, the conductor C discharges positive electricity on the plate through the comb N. In passing the comb M, a portion of this electricity is collected by the points, and charges the conductor A. The effect is increased by connecting A with another conductor E of very large dimensions.

588. Voss' Machine.—In Voss' machine, which is a modification of an earlier form invented by Holtz, the inducing charge may be indefinitely small at first, and is rapidly increased. It gives much more powerful effects than the friction machine, and is much easier to manage and keep in order. It is represented in Fig. 360.

There are two glass plates, a small distance asunder. The larger one is fixed, and the smaller one is made to revolve rapidly by means of a driving band passing over two grooved wheels, one of them much larger than the other, the larger one being turned by

hand. This plate has six metallic studs (like that at D) set in it at equal distances. The sloping bar which is seen in front of it is of brass, and carries two little brushes A A of thin brass wire, against which the studs rub as they pass by, and this happens at the same moment for both brushes. If we suppose that the fixed plate is charged with positive electricity in its upper part, and negative in its lower part, the upper stud will acquire a negative and the lower stud a positive charge, by induction, at the moment that the two

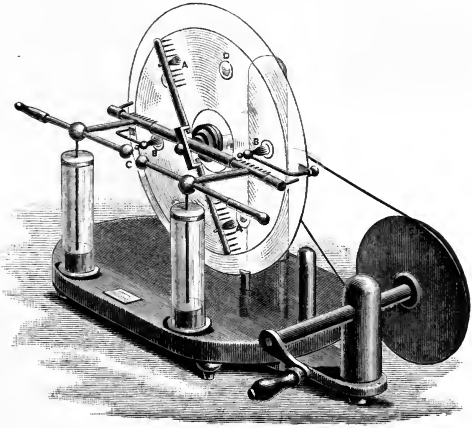

Fig. 360.—Voss Machine.

contacts occur. When the studs have advanced about a quarter of a revolution, they come in contact with another pair of brushes B B which collect their charges.

These collecting brushes are in communication with two patches of tin-foil on the back of the fixed plate, which are not shown in the figure. Thus the right-hand patch will be continually replenished with negative, and the left-hand patch with positive electricity. This left-hand patch extends to the top of the fixed plate, and acts as the influencing body to draw negative electricity to the upper brush and stud. The right-hand patch in like manner extends to the bottom, and attracts positive to the lower stud.

The action which we have described produces rapid increase of any slight charges that the two patches of tin-foil may possess at

starting; and when the machine is dry there is generally a sufficient trace of electricity remaining in it to furnish a basis for this rapid process of multiplication. In unfavourable weather it may be necessary at the outset to employ a flat piece of vulcanite (or other suitable substance), which has been electrified by friction, and hold it at the back of the fixed plate opposite the highest or lowest brush, till the machine begins to work.

When the two patches of tin-foil have acquired their charges, a great deal more electricity is produced than is necessary for keeping them up. The surplus is collected from the revolving plate by rows of brass points, just as in the friction machine. They are ranged along the two horizontal radii of the plate, one row collecting positive and the other negative. They are in connection with the two knobs C which are seen in front of the machine, and a brilliant discharge of electricity takes place between these knobs. In the above description we have supposed the right-hand patch of tin-foil to be negative. It will accordingly attract positive electricity from the right-hand conductor to the points, through which the positive electricity will stream off on to the face of the plate, leaving the conductor with a strong negative charge. The right-hand knob will therefore be negative, and the left-hand knob positive. The knobs are at the ends of sliding rods with insulating handles, and can either be placed in contact or separated to a distance of several inches. They should be about half an inch apart at starting, and be gradually opened wider as the discharge becomes stronger.

In the original Holtz machine, in place of the brushes and studs for replenishing the charges of the *armatures* (that is, the patches of tin-foil, or paper patches answering the same purpose), these armatures are furnished with projecting points of cardboard which collect electricity from the revolving plate by discharge through the air. The plate passes these cardboard points just before it passes the brass points which supply the conductors. Wimshurst has modified Voss' machine bv making the two plates revolve in opposite directions.

CHAPTER XLV.

VARIOUS EXPERIMENTS WITH THE ELECTRICAL MACHINE.

589. Electric Spark.—The spark furnished by an electrical machine of small dimensions is short, and usually straight. Powerful machines sometimes give sparks of the length of a foot. Such sparks have usually a zig-zag form, like flashes of lightning. One of the readiest means of obtaining long sparks consists in placing, opposite to one of the small knobs of the conductor of the machine, a large conductor, having good earth connection, and presenting a polished and slightly convex surface towards the knob. A more powerful effect will be obtained by connecting this conductor with the rubber or the negative conductor of the machine, instead of with the earth. Very frequently, when the spark is a foot or more in length, finer ramifications proceed from its main track, as shown in Fig. 361.

590. Brush.—When a powerful machine is working in a very dry atmosphere, the rubbers being in good order, and the machine being turned rapidly, a characteristic sound is heard, which is an indication of continuous discharge into the air. In the dark, luminous appearances called *brushes* are seen on the projecting parts of the conductors. They may be rendered very conspicuous by presenting a large conducting surface at a distance a little too great for a spark to pass. It will then be observed that the brush consists of a short foot-stalk, with a multitude of rays diverging from it like a fan, and with other smaller ramifications proceeding from these. Positive electricity gives larger and finer brushes than negative. We may add, that, when the machine is working well, brilliant sparks continually leap across the plate, consisting of discharges between the cushions and the nearest part of the conductor. The conductor itself is also surrounded with luminosity. In the dark, the brilliant spectacle presented by these combined appearances, with the con-

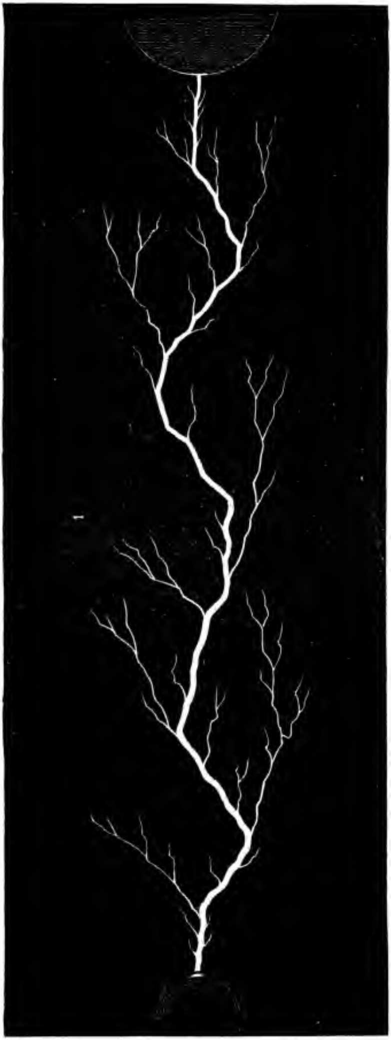

Fig. 361.—Spark with Ramifications.

tinual crackling which accompanies them, is very impressive, and furnished an inexhaustible subject of curiosity to the electricians of last century.

It is probable that the passage of a spark is always preceded by a very high degree of polar tension in all the particles of air in and about its track, and that the spark occurs when this tension anywhere exceeds what the particles are able to bear. The frequent crookedness of the spark is perhaps due to the presence of conducting particles of dust, which serve as stepping stones, and render a crooked course the easiest.

591. Duration of the Spark.—We can form no judgment of the duration of the electric spark from what we see with the unaided eye; for impressions made upon the retina remain uneffaced for something like $\frac{1}{10}$ of a second, and the duration of the spark is incomparably less than this. Wheatstone, in a

classical experiment, succeeded in measuring its duration by means of a revolving mirror; an expedient which has since been employed with great advantage in many other researches, especially in determining the velocity of light.

Let mn (Fig. 362) be a mirror revolving with great velocity about an axis passing through c, and suppose that, during the rotation, an electric spark is produced at a. An eye stationed at o will see an image in the symmetrical position a'. If the spark is strictly instantaneous, its image will be seen as a luminous point at a', notwithstanding the rotation of the mirror; but if it has a finite duration, the image will move from a' to a'', while the mirror moves from ee' to tt', the latter being its position when the spark ceases. What is actually seen in the mirror will therefore not be a point, but a luminous track $a'a''$.

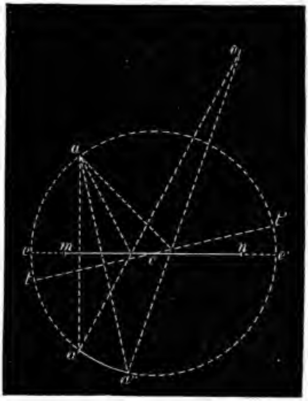

Fig. 362.—Duration of Spark.

The length of this image will be double of the arc et; for the angle ect at the centre is equal to the angle $a'aa''$ at the circumference, the sides of the one being perpendicular to those of the other. In Wheatstone's experiment, the mirror made 800 turns in a second, and the image $a'a''$ was an arc of 24°; the mirror therefore turned through 12°, or $\frac{1}{30}$ of a revolution, while the spark lasted. The duration of the spark was therefore $\frac{1}{30}$ of $\frac{1}{800}$, that is, $\frac{1}{24000}$ of a second.

By examining the brush in the same way, Wheatstone found it to consist of a succession of sparks.

592. Spark in Rarefied Gases.—The appearance of the spark is greatly modified by rarefying the air in which it is taken. To show this, an apparatus is employed which is called the *electric egg* (Fig. 363). It is an oval glass vessel, which can be exhausted by means of a stopcock at its lower end. Its upper end is closed by a cap, in which slides a brass rod terminated by a knob, which can be adjusted to any distance from another knob connected with a cap at the lower end.

When the egg contains air at atmospheric pressure, a spark passes in the ordinary way between the two knobs; but, as the pressure is diminished, the aspect of the spark changes. At a pressure of six centimetres of mercury ($\frac{1}{13}$ of an atmosphere), a sort of ramified sheaf proceeds from the positive knob, some of the rays terminating at a

Fig. 363.—Electric Egg.

Fig. 364.—Spark in Rarefied Air.

small distance from their origin, while others extend to the negative knob. The latter is surrounded with a violet glow; the rays are also violet, but with a reddish tinge. The light at the positive knob is of a reddish purple.

As the pressure is gradually reduced to a few millimetres, the rays become less distinct, and finally coalesce into an oval cloud of pale violet light, extending from one knob to the other, with a reddish tint at the positive and a deep violet at the negative end.

In performing this experiment with the ordinary electrical machine, the upper knob is connected with the conductor, and the lower one

with the ground. Holtz's machine can be very advantageously employed in experiments of this kind, its two poles being connected with the two knobs.

When, instead of the electric egg, we employ a long tube, such as is employed for showing the fall of bodies *in vacuo*, the whole length of the tube is filled with violet light, which exhibits continual flickering, and suggests the idea of undulations travelling in the same direction as the positive electricity. In all these experiments, as we diminish the density of the air, we diminish the resistance to discharge, and at the same time diminish the intrinsic brightness of the spark.

In the Torricellian vacuum, electric discharge is accompanied by a perceptible though very feeble luminosity, as may be shown by an arrangement due to Cavendish, and represented in Fig. 365. Two barometric tubes, united at the top, are plunged in two cups of mercury. The mercury in one cup is connected with the conductor of the machine, while that in the other is connected with the earth. In these circumstances, the vacuum-space is filled with luminosity, which is brighter as the temperature is higher, probably on account of the greater density of the mercurial vapour which serves as the medium of discharge.

Fig. 365.—Discharge in Torricellian Vacuum.

The experiments of Gassiot and others have shown that electricity traverses a space occupied by a gas with continually increasing facility as the density of the gas is diminished, until a certain limit is attained; but that when special means are employed to render the vacuum as nearly perfect as possible, this limit can be exceeded, and the resistance may increase so much as to prevent discharge.

This latter point is illustrated by the apparatus represented in Fig. 366, which is constructed by Alvergniat. T is a tube which has been exhausted as completely as possible by a Geissler's pump. It has

then been heated, and maintained for some time near the temperature of fusion of glass, in order to produce absorption of the remaining air. Two platinum wires have been previously sealed in the ends of the tube, and approach within $\frac{1}{10}$ of a millimetre of each other. The two poles of a Holtz's machine are connected with the binding-screws B and B′, which are in communication with these two wires, and also with two rods whose extremities *p p′* are at a moderate striking distance from each other in air. As long as the machine works, sparks pass between these latter, while, in spite of the very much closer proximity of the platinum wires, no luminosity is perceptible between them. Instead of being placed a small distance apart in air, *p* and *p′* may be fitted into the ends of a tube of considerable length containing rarefied air. It will be found that discharge can take place at greater distance as the air is more rarefied, till we attain a limit far beyond the reach of ordinary air-pumps.

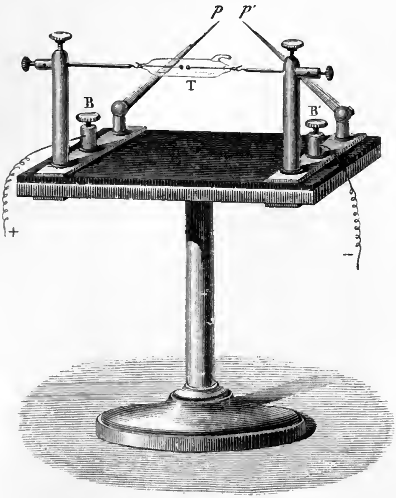

Fig. 366.—Non-conductivity of Perfect Vacuum.

593. Colour of the Spark.—The colour of the spark or other luminous discharge depends partly on the material of the conductors between which it passes, and partly on the gaseous medium which it traverses. The former influence predominates when the spark is strong, the latter when it is weak. The effect of the metal seems to depend upon the vaporization of a portion of it, for, on examining the spark by the spectroscope, bright lines are seen which are known to indicate the presence of metallic vapour. For studying the effect of the gaseous medium, the discharge is taken between two platinum wires sealed into the ends of glass tubes, containing the gases in a

rarefied condition (Fig. 367). The wires are connected either with the poles of a Holtz's machine, or of a Ruhmkorff's coil, which we shall describe in Chap. lix. It is found that the colour in air or oxygen is white with a tinge of blue, in nitrogen blue, in hydrogen red, and in carbonic acid green.

594. Multiplication of the Electric Spark.—The old electricians contrived several pieces of apparatus for multiplying the electric spark. The principle of all is the same. Small squares of tin-foil are arranged in series at a small distance from each other on an insulating surface. The first of the series is connected with a metallic knob with can be brought near the electrical machine; and the last of them is connected with another knob which is in communication with the earth. By allowing a discharge to pass through the series, sparks can be simultaneously obtained at all the intervals between the successive squares.

Fig. 367.—Tube for Rarefied Gases.

Fig. 368. Spangled Tube.

In the *spangled tube* (Fig. 368) the squares of tin-foil are arranged spirally along a cylindrical glass tube which has a brass cap at each end. One cap is put in communication with the machine, and the other with the earth.

Sometimes a glass globe is substituted for the cylinder. We have thus the *spangled globe* (Fig. 369).

In the *sparkling pane* a long strip of tin-foil is disposed in one continuous crooked line (consisting of parallel strips connected at alternate ends) from a knob at the top to another knob at the bottom of the pane. A pattern is then traced by scratching away the tin-foil in numerous places with a point, and when the spark passes, it is seen at all these places, so as to render the pattern luminous (Fig. 370).

595. Physiological Effects of the Spark: Electric Shock.—When a strong spark is drawn by presenting the hand to the conductor of a very large and powerful machine, a peculiar sensation is experienced. With ordinary machines the same effect can be obtained by

employing a Leyden jar. The sensation is difficult to describe, and only capable of being produced by electrical agency. It is a painful shock, felt especially in the arm, and causing an involuntary bending of the elbow.

At the distance of a few feet from a machine in powerful action, a tickling sensation is felt on the exposed parts of the body, due to the movement of the hairs in obedience to electrical force. These phenomena are exhibited in a still more marked manner when a

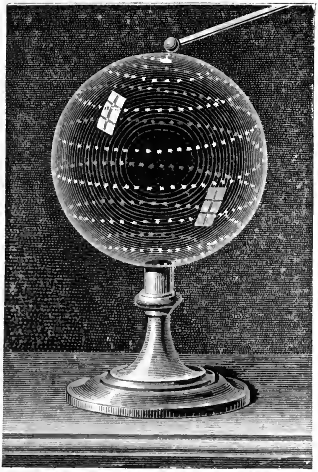

Fig. 369.—Spangled Globe.

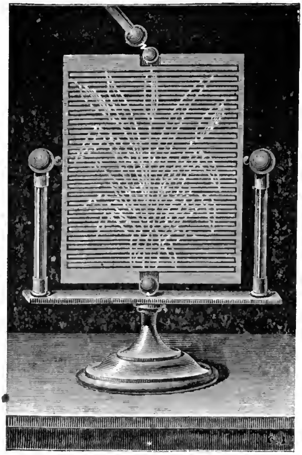

Fig. 370.—Sparkling Pane.

person stands on a stool with glass legs, and keeps his hand upon the conductor. He thus becomes highly charged with electricity. His hair stands on end, and is luminous if seen in the dark. If a conductor connected with the earth is presented to him, a spark passes, and his hair falls again.

Electricity has frequently been resorted to for medical purposes. The electrical machine was first employed, and afterwards the Leyden jar, but both have now been abandoned in favour of magneto-electric machines and other apparatus for obtaining induced currents, which we shall describe in a later chapter (Chap. lix.).

596. Mechanical and Physical Properties of the Spark.—The electric spark produces a violent commotion in the medium in which it occurs. This is easily shown by means of Kinnersley's thermometer (Fig. 371), which consists of two glass tubes of unequal diameters, the smaller being open at the top, while the larger is completely closed, with the exception of a side passage, by which it communicates with the smaller. The caps which close the ends of the large tube are traversed by rods terminating in knobs, and the upper one can be raised and lowered to vary the distance between the knobs. Both tubes are filled, to a height a little below the lower knob, with a very mobile liquid such as alcohol. When the spark passes between the knobs, the liquid is projected with great violence, and may rise

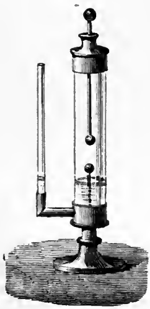

Fig. 371.—Kinnersley's Thermometer.

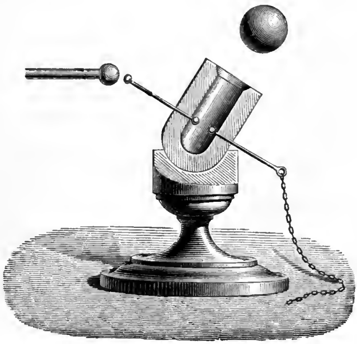

Fig. 372.—Electric Mortar.

to a height of several yards if the spark is very strong. The same property of the spark is exhibited in the experiment of the electric mortar, which is sufficiently explained by the figure (Fig. 372).

The spark may be obtained in the interior of a non-conducting liquid, which it agitates in a similar manner. If the liquid is contained in a closed vessel, this is often broken. The spark can also traverse thin non-conducting plates, producing in this case perforation of the plates; but the experiment usually requires very powerful discharges, such as can only be obtained by means of apparatus which will be described in Chapter xlvii.

The luminosity of the electric spark is probably due to the very high temperature which is produced in the particles traversed by the

discharge. Coal-gas is easily inflamed, by a person standing on a stool with glass legs holding one hand on the conductor of the machine, and giving sparks from a finger of the other hand to the burner from which the gas is issuing. Kinnersley regarded elevation of temperature as the cause of the movement of the liquid in his apparatus; hence the name which it bears.

Heating may also occur in the case of conductors. This is shown by the influence of the metal upon the colour of the spark, and it may be more directly proved by arranging a conductor in communication

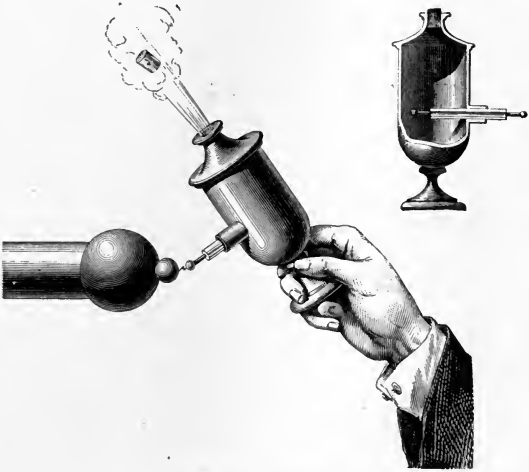

Fig. 373.—Volta's Pistol.

with the earth, and connected by an exceedingly fine metallic wire with another conductor. When the latter is presented to a very powerful electrical machine, so that a strong spark passes, the fine wire is sometimes heated to redness.

597. Chemical Properties of the Spark.—The electric spark is able to produce very important chemical effects. When it occurs in an explosive mixture of two parts of hydrogen with one of oxygen, it causes these gases instantly to combine. This experiment is usually shown by means of Volta's pistol (Fig. 373), which is a metallic vessel, containing the mixture, and closed by a cork. Through one side

passes an insulated metallic rod with a knob at each end, that at the inner end being at a short distance from the opposite side of the vessel, so that, if a spark is given to the exterior knob, a spark also passes in the interior, and inflames the mixture. This effect is accompanied by a violent detonation, and the cork is projected to a distance.

The electric spark often produces a reverse effect—that is to say, the decomposition of a compound body; but the action in this case is gradual, and a great number of sparks must be passed before the full effect is obtained. Thus, if a succession of sparks be passed in

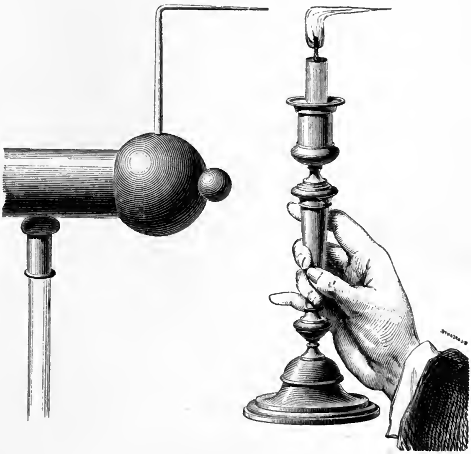

Fig. 374.—Wind from Points.

the interior of a mass of ammonia, contained in a vessel inverted over mercury, the volume of the gas is observed to undergo a gradual increase, until at length, if kept at constant pressure, the volume is exactly doubled. It then consists of a mechanical mixture of nitrogen and hydrogen, the constituents of ammonia.

Composition and decomposition are often both produced at once. Thus, if a spark is passed in a mixture of carburetted hydrogen and a certain proportion of oxygen, the former gas is decomposed, its hydrogen combining with a portion of the oxygen to form water, and its carbon combining with another portion to form carbonic acid.

598. Wind from Points.—If a metallic rod terminating in a point be attached to the conductor of the electrical machine, electricity escapes in large quantity from the point, which, accordingly, when viewed in the dark, is seen to be crowned with a tuft of light. A layer of air in front of the point is electrified by contact, and then repelled, to make way for other portions of air, which are in their turn repelled. A continuous current of air is thus kept up, which is quite perceptible to the hand, and produces a very visible effect on the flame of a taper (Fig. 374).

The *electric whirl* (Fig. 375) consists of a set of metallic arms, radiating horizontally from a common centre about which they can turn freely, and bent, all in the same direction, at the ends, which are pointed. When the central support is mounted on the conductor of the machine, the arms revolve in a direction opposite to that in which their ends point. This effect is due to the mutual repulsion between the pointed ends and the electrified air which flows off from them.

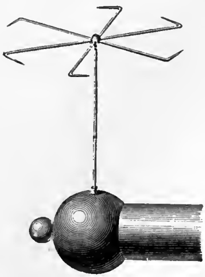

Fig. 375.—Electric Whirl.

It is instructive to remark that if, by a special arrangement, the rotating part be inclosed in a well-insulating glass case, the rotation soon ceases, because, in these circumstances, the inclosed air quickly attains a state of permanent electrification.

599. Electric Watering-pot.—Let a vessel containing a liquid, and furnished with very fine discharge tubes, be suspended from the conductor of the machine. When the vessel is not electrified, the liquid comes out drop by drop; but when the machine is turned, it issues in continuous fine streams. It has, however, been observed that the quantity discharged in a given time is sensibly the same in both cases. This must be owing to the equality of action and reaction between different parts of the issuing stream.

Fig. 376.—Electric Bucket.

CHAPTER XLVI.

ELECTRICAL POTENTIAL, AND LINES OF ELECTRICAL FORCE.

600. The object of the present chapter is to give a brief outline of the methods by which mathematicians have succeeded in bringing numerous electrical problems within the range of accurate reasoning.

The fundamental conception in the mathematical theory of electricity is that of attraction and repulsion, acting according to the law of inverse squares; and the unit quantity of electricity is defined to be that quantity which would attract or repel an equal quantity at unit distance with unit force.

The influence which an electrified body exercises in the region around it can be specified by stating the force of attraction or repulsion which the body would exert upon a small charged body placed in various parts of this region or field (which is accordingly called a field of electrical force), the force being stated not only in magnitude but also in direction. In this sense we speak of *the electrical force at a point,* meaning the force which would be exerted upon a unit of electricity placed at the point; and in any such specification the unit of electricity is supposed not to disturb by its presence the previously existing distribution of electricity.

There can be electrical force at points in the air, or in the substance of any non-conductor, without disturbance of equilibrium; but electrical force in a conductor instantly produces a current of electricity in the direction of the force. At the *surface* of a conductor electrical force can exist, but it must always be normal to the surface; for if there were any tangential component, a current would be produced along the surface.

601. Definition of Difference of Potential.—We know, by the principle of the conservation of energy, that the work done upon a unit

of electricity in its passage from one point to another, must be independent of the path pursued; and we agree to call this work the difference of potential of the two points.

602. Relation between Potential and Force.—If V denote the potential at a point, and $V - \delta V$ the potential at a neighbouring point, δV is the work which electrical attractions and repulsions do upon a unit of positive electricity in its passage from the first point to the second; and since work is equal to force multiplied by distance, the average force along the joining line can be computed by dividing δV by the distance, which we will call δs. Hence the limiting value of $\frac{\delta V}{\delta s}$ as the two points are taken nearer together, is the component force in the direction δs; that is, *the rate of variation of potential in any direction is equal to the component force in that direction.*

The direction in which the variation is most rapid will be the direction of the resultant force; and when δs is measured in this direction $\frac{\delta V}{\delta s}$ will be equal to the resultant force.

603. Lines of Force.—If a line be traced such that every small portion of it (small enough to be regarded as straight) is the direction of resultant force at the points which lie upon it, it is called a line of force; in other words, a line of force is a line whose tangent at any point is the direction of the force at that point. We may express this briefly by saying that lines of force are the lines along which resultant force acts.

604. Equipotential Surfaces.—An equipotential surface is a surface over the whole of which there is the same value of potential. When δs lies in such a surface, the value of $\frac{\delta V}{\delta s}$ is zero; and therefore there is no component force along any line lying in the surface. The resultant force must therefore be normal; that is, *lines of force cut equipotential surfaces* at right angles.

When we are dealing with gravitational forces instead of with electrical attractions and repulsions, equipotential surfaces are called *level* surfaces, and lines of force are called *verticals.*

If two equipotential surfaces are given, their potentials being V_1 and V_2, the work done in carrying a unit of electricity from any point of the one to any point of the other, is constant, and equal to the difference of V_1 and V_2.

If we consider two equipotential surfaces very near one another, so that the portions which they intercept on the lines of force may

be regarded as straight, the intensity of force at different points of the intermediate space will vary inversely as the distance between the two equipotential surfaces; for, when equal amounts of work are done in travelling unequal distances, the forces must be inversely as the distances.

605. Potential of a Conductor.—When electrical potential is constant throughout a given space, there is no electrical force in that space; and conversely, if there be an absence of electrical force in a given space, the potential throughout that space must be uniform. These propositions apply to the space within a hollow conductor. They also apply to the whole substance of a solid conductor, and to the whole space inclosed within the outer surface of a hollow conductor. Whenever a conductor is in electrical equilibrium, it has the same potential throughout the whole of its substance, and also through any completely inclosed hollows which it may contain.

When a conductor is not in electrical equilibrium, currents set in, tending to restore equilibrium; and the direction of such currents is always from places of higher to places of lower potential.

It is usual to assume as the zero of potential the potential of the earth; but this assumption is not consistent with itself, since the existence of earth currents proves that there are differences of potential between different parts of the earth. The absolute zero of potential is the potential of places infinitely distant from all electricity.

606. Energy of a Charged Conductor.—When positive electricity is allowed to run down from a conductor of higher to one of lower potential, there is a loss of potential energy, just as there is a loss of potential energy in the running down of a heavy body from a higher to a lower level; and on the other hand, to make positive electricity pass from a conductor of lower to one of higher potential, work must be expended from some external source, just as work must be expended to raise a heavy body. In the case of the heavy body, the work expended in the latter case, or the potential energy which runs down in the former, is equal to its weight multiplied by the difference of levels; and in the analogous case of the electrical operation, the work or the energy is the product of the quantity of electricity which passes from one conductor to the other by the difference of potentials of the two conductors,[1] provided that these potentials remain sensibly constant during the operation.

[1] The closeness of the analogy will be better understood when it is remembered that if

When a conductor is charged in the ordinary way, its charge is drawn from the earth, the potential of which is unaffected. If we suppose the charge to be communicated in a numerous succession of small equal parts, the potential of the conductor, which is originally zero, is increased by a succession of equal steps, till it attains its final value. Hence it is only the last part that is raised through the full difference of potential, and the mean value of the difference of potential through which the successive parts are raised is the half of this. Hence the work done in charging a conductor, or the energy which runs down in discharging it into the earth, is half the product of its potential and its charge.

607. Tubes of Force.—If we conceive a narrow tube bounded on all sides by lines of force, and call it a *tube of force*, we can lay down the following remarkable rules[1] for the comparison of the forces which exist at different points in its length. (1) *In any portion of a tube of force not containing electricity, the intensity of force varies inversely as the cross-section of the tube*, or the product of *intensity of force by section of tube* is constant.[2] (2) *When a tube of force cuts through electricity, this product changes, from one side of this electricity to the other, by the amount* $4\pi q$, where q denotes the quantity of the electricity inclosed by the tube.

The following are particular cases of (1):—

When the electricity to which the force is due is collected in a point, the lines of force are straight, the tubes of force are cones (in the most general sense), and the law of force becomes the law of inverse squares, since the section of a cone varies as the square of the

a series of level surfaces are described completely surrounding the earth, and one foot apart at the equator, they will be less than a foot apart at the poles, for the distance between them will, by the reasoning in the text, be inversely as the intensity of gravity. The work done in lifting a body from any one of these surfaces to any other, will be proportional to the product of its mass (not its weight) by the number of intervals crossed.

If one of the surfaces passes through the top of Mount Everest, and another through a point on the Indian coast, the distance between them will be greater at the coast than at the mountain. Hence the height of the mountain above the coast is an ambiguous quantity.

[1] For the proof of these rules, as mathematical deductions from the law of inverse squares, the student may refer to Everett's edition of Todhunter's *Analytical Statics*, articles 228, 235.

[2] This is obviously analogous to the law which applies to the comparison of the velocities of a liquid in different parts of a tube through which it flows, since the product of area by velocity is the volume of liquid which flows past any section in unit time. The tube may be an imaginary one, bounded by lines of flow in a large body of liquid flowing steadily. Lines of flow are thus the analogues of lines of force.

distance from the vertex. These results also apply to the case of electricity uniformly distributed over the surface of a sphere, the common vertex in which the cones would meet if produced being now at the centre of the sphere.

When the electricity consists of the charges of two oppositely electrified parallel plates, whose length and breadth exceed the distance between them (the plates being conductors, and placed opposite to each other), the lines of force between their central portions are sensibly straight and parallel, the tubes of force are therefore cylinders (in the most general sense), and the force is constant, being equal to the difference of the potentials of the plates divided by the distance between them. The same thing holds if, instead of being oppositely electrified, the plates are similarly electrified, but not to the same potential.

608. Force Proportional to Number of Tubes which cut Unit Area.—The cross-sections of tubes of force are portions of equipotential surfaces. If one equipotential surface be divided into portions, such that the product of *area by force-intensity* shall be the same for all, then, if all neighbouring space not containing electricity be cut up into tubes, springing from these portions as their respective bases, the product of any cross-section of any one of these tubes by the force-intensity over it will be constant. The force-intensities at any points in this space are therefore inversely as the cross-sections of the tubes at these points, or are directly as the number of tubes per unit area of equipotential surfaces at the points.

609. Force just Outside an Electrified Conductor.—Since there is no force in the interior of a conductor, the lines and tubes of force become indeterminate; but proposition (2) of § 607 can be shown to hold when we give them any shape not discontinuous. Let ρ denote the electric density at a point on the surface, and a a small area around this point, which area we shall regard as a section of a tube of force cutting through the surface. Let F denote the intensity of force just outside the surface opposite this point, then, since the intensity inside is zero we have

$$\mathrm{F}a=4\pi q=4\pi\rho a \quad , \quad \mathrm{F}=4\pi\rho;$$

that is, *the intensity of force just outside any part of the surface of a charged conductor, is equal to the product of* 4π *into the density at the nearest part of the surface.*

610. Relation of Induction to Lines and Tubes of Force.—Lines of

force are also the lines along which induction takes place. On Faraday's theory of induction by contiguous particles, the line of poles, for any particle, is coincident with the line of force which passes through the particle. Apart from all theory, it is matter of fact that *a tube of force extending from an influencing to an influenced conductor, and not containing any electricity in the interval between, has equal quantities of electricity on its two ends, these quantities being of opposite sign.* This equality follows at once from § 607 (2), if we consider the tube as penetrating the two conductors; for the product of force by section, which is constant for the portion of the tube in air, is zero in both conductors; and the quantity of electricity on *either* end of the tube must be the quotient of this constant product by 4π. In connection with this reasoning, it is to be remarked that the surface of a conductor is an equipotential surface, and is cut at right angles by lines of force.

In Faraday's ice-pail experiment, a tube of force springing from the upper side of the charged ball, and of such small section at its origin as to inclose only an insensible fraction of the charge of the ball, opens out so fast, as it advances, that it fills the whole opening at the top of the pail.

In every case of induction, therefore, *the total quantities of inducing and induced electricity are equal, and of opposite sign.*

When the inducing electricity resides in or upon a non-conductor, for example on the surface of a glass rod, or in the substance of a mass of air, the quantity of electricity induced on the base of a tube of force is equal and opposite to the quantity contained within the tube. In the simplest case, all the tubes will have a common apex, which will be a point of maximum or minimum potential.

611. Potential defined as $\Sigma \frac{q}{r}$.

Let a quantity q of electricity be collected at a point O, and let A, B be any two points very near together. The forces at A and B due to q will be $\frac{q}{OA^2}$ and $\frac{q}{OB^2}$, and these will be nearly equal to each other or to $\frac{q}{OA \cdot OB}$. When a unit of electricity is carried from A to B its motion can be resolved into two components, one of them in the direction of the force and equal to $OB - OA$, and the other perpendicular to the direction of the force. Hence the work done will be $\frac{q(OB-OA)}{OA \cdot OB}$, that is, $\frac{q}{OA} - \frac{q}{OB}$; or if r denote the distance of any point from O, the *work done in a* small *movement is equal to*

the change in the value of $\frac{q}{r}$. Since any movement can be resolved into a succession of small movements, we may omit the word *small*, and the proposition will still be true. As r increases to infinity, $\frac{q}{r}$ will diminish to zero. Hence, $\frac{q}{r}$ denotes the work from distance r to infinite distance.

As regards sign, $\frac{q}{r}$ is the work done by electrical force when a unit of positive electricity is carried from distance r to infinite distance.

Next suppose several quantities, q_1, q_2, &c., to be collected at different points, O_1, O_2, &c. Let P be any other point, and let $O_1P = r_1$, $O_2P = r_2$, &c. Then in the passage of a unit of electricity from P to infinite distance, the electrical work is, by the preceding section,

$$\frac{q_1}{r_1} + \frac{q_2}{r_2} + \quad \&c.,$$

which we will denote by $\Sigma \frac{q}{r}$, the symbol Σ being read "the sum of such terms as."

$\Sigma \frac{q}{r}$ is therefore the general expression for the potential at a point due to any quantity of electricity distributed in any manner; in other words, the potential is equal to the sum of the quotients obtained by dividing each element of electricity by its distance from the point. The distances are essentially positive. If the electricity is not all of one sign, some of the quotients, $\frac{q}{r}$, will be positive and others negative, and their algebraical sum is to be taken.

612. Application to Sphere.—In the case of a charged conducting sphere, all the elements q are equally distant from the centre of the sphere, and the sum of the quotients $\frac{q}{r}$, when we are computing the potential at the centre, will be $\frac{Q}{R}$, Q denoting the charge, and R the radius of the sphere. But the potential is the same at all points in a conductor. $\frac{Q}{R}$ is therefore the potential of a sphere of radius R, with charge Q, when uninfluenced by any other electricity than its own.

613. Capacity.—The electrical capacity of a conductor is *the quantity of electricity required to charge it to unit potential,* when it is not influenced by any other electricity besides its own charge and the electricity which this induces in neighbouring conductors. Or,

since, in these circumstances, potential varies directly as charge, capacity may be defined as the *quotient of charge by potential.* Let C denote capacity, V potential, and Q charge, then we have

$$C = \frac{Q}{V} \quad ; \quad V = \frac{Q}{C} \quad ; \quad Q = VC.$$

But we have seen that, for a sphere of radius R, at a distance from other conductors or charged bodies, $V = \frac{Q}{R}$. Hence $C = R$; that is, the *capacity of a sphere is numerically equal to its radius.*

This is a particular instance of the general proposition that the capacities of similar conductors are as their linear dimensions; which may be proved as follows:—

Let the linear dimensions of two similar conductors be as $1 : n$. Divide their surfaces *similarly* into very small elements, which will of course be equal in number. Then the areas of corresponding elements will be as $1 : n^2$, and, if the electrical densities at corresponding points be as $1 : x$, the charges on corresponding elements are as $1 : n^2x$. The potential at any selected point of either conductor is the sum of such terms as $\frac{q}{r}$ (§ 611). Selecting the corresponding point in the other conductor, and comparing potentials, the values of q are as $1 : n^2x$, and the values of r are as $1 : n$; therefore the values of $\frac{q}{r}$ are as $1 : nx$. Hence the potentials of the two conductors are as $1 : nx$. If they are equal, we have $nx = 1$, and therefore $n^2x = n$; that is, the charges on corresponding elements, and therefore also on the whole surfaces, are as $1 : n$.

We shall see, in the next chapter, that the capacity of a conductor may be greatly increased by bringing it near to another conductor connected with the earth.

614. Connection between Potential and Induced Distribution.—In the circumstances represented in Fig. 335 (§ 563), if we suppose the influencing body C to be positively charged, the potential due to this charge will be algebraically greater at the near end A of the influence conductor than at the remote end B. The induced electricity on A B must be so distributed as to balance this difference, in fact the potential due to this induced electricity is negative at A and positive at B. All cases of induced electricity upon conductors fall under the rule that *the potential at all parts of a conductor must be the same, and hence, wherever the potential due to the influencing*

electricity is algebraically greatest, the potential due to the electricity on the influenced conductor must be algebraically least.

As there can be no force in the interior of a conductor, the force at any point in the interior, due to the influencing electricity, must be equal and opposite to the force due to the electricity on the surface of the conductor. This holds, whether the conductor be solid or hollow. A hollow conductor thus completely screens from external electrical forces all bodies placed in its interior.

615. Electrical Images.—If a very large plane sheet of conducting material be connected with the earth, and an electrified body be placed in front of it near its middle, the plate will completely screen all bodies behind it from the force due to the electrified body. The induced electricity on the plate therefore exerts, at all points behind the plate, a force equal and opposite to that of the electrified body, or, what is the same thing, a force identical with that which the electrified body would exert if its electricity were reversed in sign. But electricity distributed over a plane surface must act symmetrically towards both sides. Hence the force which the induced electricity exerts in front, is identical with that which would be exerted by a body precisely similar to the given electrical body, symmetrically placed behind the plane, and charged with the opposite electricity. The total force at any point in front of the plane is the resultant of the force due to the given electrified body, and the force due to this imaginary image. The name and the idea of *electrical images*, of which this is one of the simplest examples, are due to Sir W. Thomson.

CHAPTER XLVII.

ELECTRICAL CONDENSERS.

616. Condensers.—The process called *condensation of electricity* consists in increasing the capacity of a conductor by bringing near it another conductor connected with the earth. The two conductors are usually thin plates or sheets of metal, placed parallel to one another, with a larger plate of non-conducting material between them.

Let A and B (Fig. 377) be the two conducting plates, of which A, called the *collecting plate*, is connected with the conductor of the machine, and B, called the *condensing plate*, with the earth; and let C be the non-conducting plate (or dielectric) which separates them. Then, if the machine has been turned until the limit of charge is attained, the surface of B which faces towards A is covered with negative electricity, drawn from the earth, and held by the attraction of the positive electricity of A; and, conversely, the surface of A which faces towards B, is covered with positive electricity, held there by the attraction of the negative of B, in addition to the charge which would reside upon it if the conductor were at the existing potential, and B and C were absent. In fact, the electrical density on the face of A, as well as the whole charge of A, would, in this latter case, be almost inappreciable, in comparison with those which exist in the actual circumstances. By condensation of electricity, then,

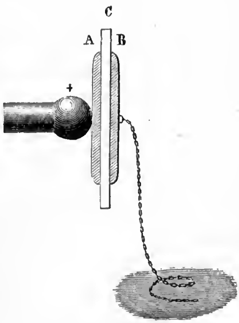

Fig. 377.—Theoretical Condenser.

we are to understand *increase*—usually enormous increase—*of electrical density on a given surface, attained without increase of potential.* If two conducting plates, in other respects alike, but one with, and the other without a condensing plate, be connected by a wire, and the whole system be electrified, the two plates will have the same potential, but nearly the whole of the charge will reside upon the face of that which is accompanied by a condensing plate.

617. Calculation of Capacity of Condenser.—The lines of force between the two plates A and B are everywhere sensibly straight and perpendicular to the plates, with the exception of a very small space round the edge, which may be neglected. The tubes of force (§ 607) are therefore cylinders, and the intensity of force is constant at all parts of their length. Also, since the potential of the plate B is zero, if we take V to denote the potential of the plate A, which is the same as the potential of the conductor, and t to denote the thickness of the intervening plate C, the rate at which potential varies along a line of force is $\frac{V}{t}$, which is therefore (§ 602) the expression for the force at any point between the plates A, B. The whole space between the plates may be regarded as one cylindrical tube of force of cross-section S equal to the area of either plate, the two ends of the tube being the inner faces of the plates. The quantities of electricity $\pm$ Q residing on these faces are therefore equal, but of opposite sign (§ 610); and as the force changes from nothing to $\frac{V}{t}$ in passing from one side to the other of the electricity which resides on either of these surfaces, we have (§ 607)

$$\frac{V}{t} . S = 4 \pi Q.$$

Hence the capacity of the plate A, being, by definition, equal to $\frac{Q}{V}$, is equal to

$$\frac{S}{4 \pi t}.$$

We should, however, explain that, if the intervening plate C is a solid or liquid, we are to understand by t not the simple thickness, but the thickness reduced to an equivalent of air, in a sense which will be explained further on (§ 624). This reduced thickness is, in the case of glass, about half the actual thickness.

If s denote an element of area of A, and q the charge residing

upon it, it is evident, from considering the tube of force which has s for one of its ends, that

$$\frac{V}{t} \cdot s = 4 \pi q;$$

and the electric density $\frac{q}{s}$ on the element is equal to $\frac{V}{4 \pi t}$, which is constant over the whole face of the plate.

To give a rough idea of the increase of capacity obtained by the employment of a condensing plate, let us compare the capacity of a circular disc of 10 inches diameter, accompanied by a condensing plate at a reduced distance of $\frac{1}{20}$ of an inch, with the capacity of a globe of the same diameter as the disc. The capacity of the globe is equal to its radius, and may therefore be denoted by 5. The capacity of the disc is $\frac{25 \pi}{4 \pi \times \frac{1}{20}} = 125$, or 25 times the capacity of the globe. It is, in fact, the same as the capacity of a globe 250 inches (or 20 ft. 10 in.) in diameter.

618. Discharge of Condenser.—If, by means of a jointed brass discharger (Fig. 378) with knobs M N at the ends, and with glass

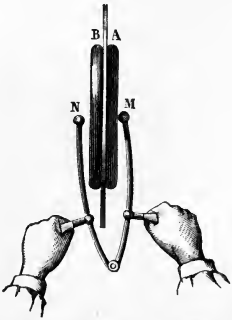

Fig. 378.—Discharge of Condenser.

Fig. 379.—Discharger without Handles.

handles, we put the two plates A and B in communication, a brilliant spark is obtained, resulting from the combination of the positive charge of A with the negative of B, and the condenser is discharged. When the quantity of electricity is small, the glass handles are unnecessary, and the simpler apparatus represented in Fig. 379 may be employed, consisting simply of two brass rods jointed together, and with knobs at their ends, care being taken to touch the plate B, which is in communication with the earth, before the other. The

operator will then experience no shock, as the electricity passes in preference through the brass rods, which are much better conductors than the human body. If, however, the operator discharges the condenser with his hands by touching first the plate B, and then also the plate A, the whole discharge takes place through his arms and chest, and he experiences a severe shock. If he simply touches the plate A, while B remains connected with the earth by a chain, as in Fig. 377, he receives a shock, but less violent than before, because the discharge has now to pass through external bodies which consume a portion of its energy. If, instead of a chain, B is connected with the earth by the hand of an assistant touching it, he too will receive a shock when the operator touches A.

619. Discovery of Cuneus.—The invention of the Leyden jar was brought about by a shock accidentally obtained. Some time in the

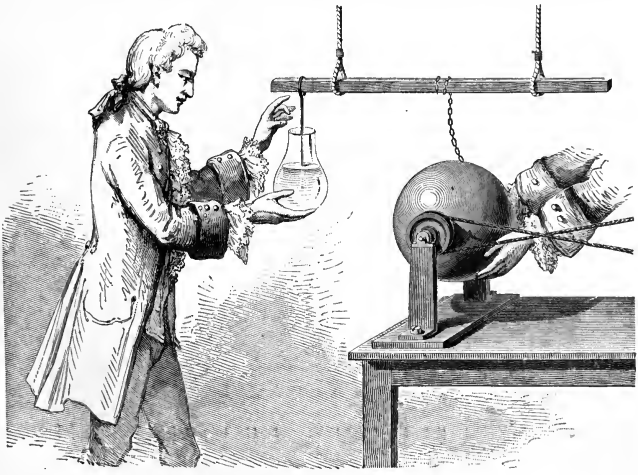

Fig. 380.—Experiment of Cuneus.

year 1746, Cuneus, a pupil of Muschenbroeck, an eminent philosopher of Leyden, wishing to electrify water, employing for this purpose a wide-mouthed flask, which he held in his hand, while a chain from the conductor of the machine dipped in the water (Fig. 380). When the experiment had been going on for some time, he wished to disconnect the water from the machine, and for this purpose was about

to lift out the chain; but, on touching the chain, he experienced a shock, which gave him the utmost consternation, and made him let fall the flask. He took two days to recover himself, and wrote to Réaumur that he would not expose himself to a second shock for the crown of France. The news of this extraordinary experiment spread over Europe with the rapidity of lightning, and it was eagerly repeated everywhere. Improvements were soon introduced in the arrangement of the flask and its contents, until it took the present form of the *Leyden Phial* or *Leyden Jar.* It is easy to see that the effect obtained by Cuneus depended on condensation of electricity, the water in the vessel serving as the collecting plate, the hand as condensing plate, and the vessel itself as the dielectric. When he

Fig. 381.—Leyden Jar.

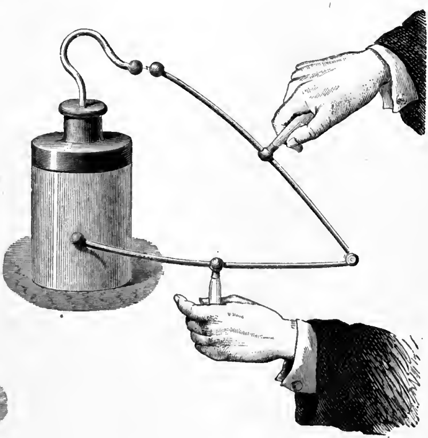

Fig. 382.—Discharge of Leyden Jar.

touched the chain, the two oppositely charged conductors were put in communication through the operator's body, and he received a shock.

620. Leyden Jar.—The Leyden jar, as now usually constructed, consists of a glass jar coated, both inside and out, with tin-foil, for

about four-fifths of its height. The mouth is closed by a cork, through which passes a metallic rod, terminating above in a knob, and connected below with the inner coating, either by a chain depending from it, or by pieces of metallic foil with which the jar is filled. The interior of the jar must be thoroughly dry before it is closed, and the cork and neck are usually covered with sealing-wax, and shellac varnish, which is less hygroscopic than glass. The Leyden jar is obviously a condenser, its two coatings of tin-foil performing the parts of a collecting plate and a condensing plate. If the inner coating is connected with the electrical machine, and the outer coating with the earth, the former acquires a positive, and the latter a negative charge. On connecting them by a discharger, as in Fig. 382, a spark is obtained, whose power depends on the potential of the inner coating, and on its electrical capacity. If these be denoted respectively by V and C, and if Q denote the quantity of electricity residing on either coating, the amount of electrical energy which runs down and undergoes transformation when the jar is discharged, is $\frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$. (§ 606.)

The quantities Q, V, C, which are, properly speaking, the charge, potential, and capacity of the *inner coating*, are usually called the charge, potential, and capacity of the jar.

621. Residual Charge.—When a Leyden jar has been discharged by connecting its two coatings, if we wait a short time we can obtain another but much smaller spark by again connecting them, and other sparks may sometimes be obtained after further intervals. These are called secondary discharges, and the electricity which thus remains after the first discharge is called the *residual charge*. It appears to arise from a state of strain into which the glass is thrown by the charge, and from which it takes some time to recover.

The whole charge of the outer coating, and all except an insignificant portion of the charge of the inner coating, resides on the side of the foil which is in contact with the glass, or, more probably, on the surfaces of the glass itself, the mutual attraction of the two opposite electricities causing them to approach as near to each other as the glass will permit. This is illustrated by Franklin's experiment of the *jar with movable coatings* (Fig. 383). The jar is charged in the ordinary way, and placed on an insulating stand. The inner coating is then lifted out by a glass hook, and touched with the hand to discharge it of any electricity which it may retain. The

glass is then lifted out, and the outer coating also discharged. The jar is then put together again, and is found to give nearly as strong a spark as it would have given originally.

Fig. 383.—Jar with Movable Coatings.

622. Discharge by Alternate Contacts.—Instead of discharging a Leyden jar at once by connecting its two coatings, we may gradually discharge it by alternate contacts. To do this we must set it on an insulating stand (or otherwise insulate both coatings from the earth), and then touch the two coatings alternately. At every contact a small spark will be drawn. The coating last touched has always rather less electricity upon it than the other, but the difference is an exceedingly small fraction of the whole charge, and, after a great number of sparks have been drawn by these alternate contacts, we may still obtain a powerful discharge by connecting the two coatings.

The quantities of electricity thus alternately discharged from the two coatings form two decreasing geometric series, one for each coating. In fact, if m and m' be two proper fractions such that, when the outer coating is connected with the earth, the ratio of its charge to that of the inner is $-m$; and, when the inner coating is connected with the earth, the ratio of its charge to that of the outer is $-m'$, we have the following series of values:—

	On inner coating.		On outer coating.
Original charges,	$+ Q$	...	$- m Q$
After 1st contact,	$+ m'm Q$	...	$- m Q$
2d "	$+ m'm Q$	...	$- m'm^2 Q$
3d "	$+ m'^2m^2 Q$	...	$- m'm^2 Q$
	&c.		&c.

The quantities discharged from the inner coating are, successively $(1-m'm)$ Q, $m'm$ $(1-m'm)$ Q, m'^2m^2 $(1-m'm)$ Q, &c.; and the quantities successively discharged from the outer, neglecting sign, are m $(1-m'm)$ Q, $m'm^2$ $(1-m'm)$ Q, m'^2m^3 $(1-m'm)$ Q, &c.

The quantity $(1-m'm)$ Q discharged at the first contact represents that portion of the charge[1] which is not due to condensation; so

[1] This portion of the original charge is said to be *free*, and the remaining portion to be *bound, dissimulated*, or *latent*. These terms are applicable to all cases of condensation.

Than one whose plates are farther apart,

dont mult

that the actual capacity of the Leyden jar is to the capacity of the inner coating if left to itself as $1 : 1 - m'm$.

The discharge by alternate contacts can be effected by means of a carrier suspended between two bells, as in Fig. 384. The rod from the inner coating terminates in a bell, and the outer coating is connected, by means of an arm of tin, with another bell supported on a metallic column. An insulated metallic ball is suspended between the two. This is first attracted by the positive bell. Then, being repelled by this and attracted by the other, it carries its charge of positive electricity to the negative bell, and receives a charge of negative, which it carries to the positive bell, and so on alternately. The whole apparatus stands upon an insulating support. It is not, however, necessary that the carrier should be insulated from the earth, but it must be insulated from both coatings.

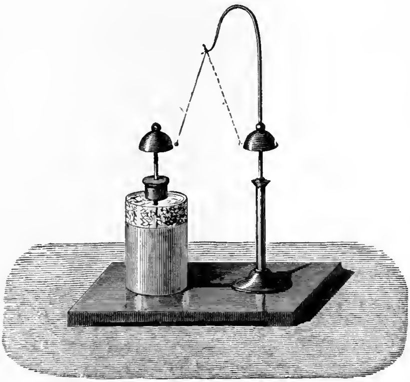

Fig. 384.—Alternate Discharge.

623. Condensing Power.—By the condensing power of a given arrangement is meant the ratio in which the capacity of the collecting plate is increased by the presence of the condensing plate, which ratio, as we have seen in last section, is equal to the fraction $\frac{1}{1-m'm}$. Riess has investigated its amount experimentally under varying conditions, by means of the apparatus represented in Fig. 385, which is a modification of the condenser of Æpinus. It consists of two metallic plates A and B, supported on glass pillars, and travelling on a rail, so that they can be adjusted at different distances. Between them is a large glass plate C. A is charged from the machine, B being at the same time touched to connect it with the ground. The electrical density on the anterior face of A was observed by means of Coulomb's proof-plane and torsion-balance.

Riess' experiments are completely in agreement with the theory laid down in the preceding sections of this chapter; for example, he found, among other results, that the condensing power was independent of

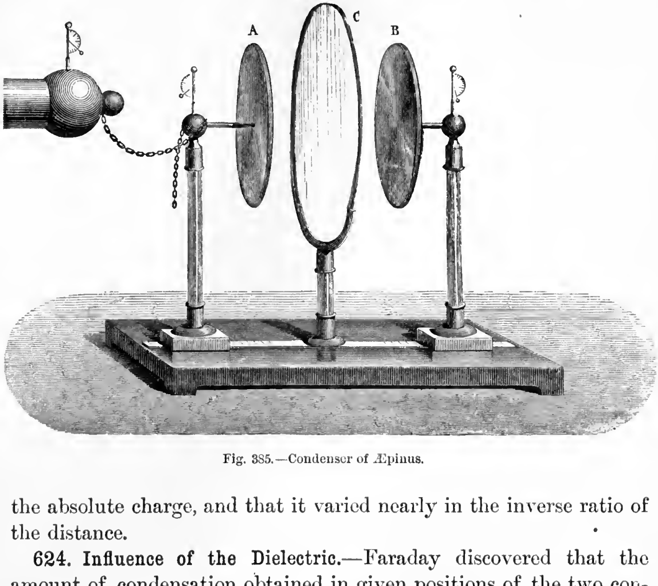

Fig. 385.—Condenser of Æpinus.

the absolute charge, and that it varied nearly in the inverse ratio of the distance.

624. Influence of the Dielectric.—Faraday discovered that the amount of condensation obtained in given positions of the two conducting plates depended upon the material of the *intervening non-conductor* or *dielectric*. Fig. 386 represents a modification of one of Faraday's experiments. A is an insulated metallic disc, with a charge, which we will suppose to be positive. B and C are two other insulated metallic discs at equal distances from A, each having a small electric pendulum suspended at its back. Let B and C be touched with the hand; they will become negatively electrified by induction, but their negative electricity will reside only on their sides which face towards A, and the pendulums will hang vertically. If, while matters are in this condition, we move B nearer to A, we shall see both the pendulums diverge, and on testing, we shall find that the pendulum B diverges with positive, and C with negative electricity. The reason is obvious. The approach of B to

A causes increased induction between them, so that more negative is drawn to the face of B, and positive is driven to its back; at the same time the symmetrical distribution of electricity on A is disturbed, a portion being accumulated on the side next B at the expense of the side next C. The inductive action of A upon C is thus diminished, and a portion of the negative charge of C is left free to spread itself over the back, and affect the pith-ball.

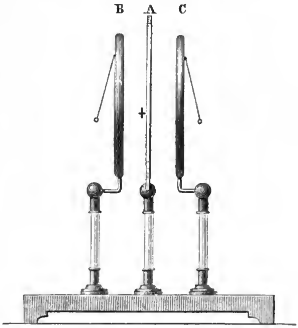

Fig. 386.—Change of Distance.

If, while the discs are in their initial position, B and C being equidistant from A, and the pendulums vertical, we interpose between B and A a plate of sulphur, shellac, or any other good insulator, the same effect will be produced as if B had been brought nearer to A. We see, then, that the insulating plate of a condensing arrangement serves not only to prevent discharge, but also to increase the inductive action and consequent condensation, as compared with a layer of air of the same thickness; inductive action through a plate of sulphur or shellac of given thickness, is the same as through a thinner plate of air. The numbers in the subjoined table (which contains Faraday's results) denote the thickness of each material which is equivalent to unit thickness of air. For example, the mutual induction through 2·24 inches of sulphur is the same as through 1 inch of air. These numbers are called

Specific Inductive Capacities.

Air or any gas,	1·00	Pitch,	1·80
Spermaceti,	1·45	Wax,	1·86
Glass,	1·76	Shellac,	2·00
Resin,	1·77	Sulphur,	2·24

The quotient of the actual thickness of the plate by the specific inductive capacity of its material may appropriately be called the *thickness reduced to its equivalent of air*, or simply the *reduced thickness.*

When the comparisons are made by very rapid charges and dis-

charges (so as to minimize the residual charge), larger values are found; for example,—

Glass,	7 to 9	India-rubber,	2
Shellac,	3·4	„ vulcanized,	2·8
Sulphur,	3	Ebonite,	2·6
Solid paraffin,	2	Turpentine,	2·2

625. **Faraday's Determinations.**—Faraday, to whom the name and discovery of specific inductive capacity are due, operated by comparing the capacities of condensers, alike in all other respects, but differing in the materials employed as dielectrics. One of his condensers is represented in Fig. 387. It is a kind of Leyden jar, containing a metallic sphere A, attached to the rod M, and forming with it the inner conductor. The outer conductor consists of the hollow sphere B divided into two hemispheres which can be detached from each other. The interval between the outer and inner conductor can be filled, either with a cake of solid non-conducting material, or with gas, which can be introduced by means of the cock R. The method of observation and reduction will be best understood from an example.

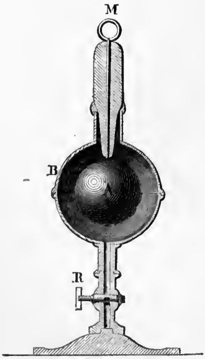

Fig. 387.—Apparatus for Specific Inductive Capacity.

The interval being occupied by air, the apparatus was charged, and a carrier-ball, having been made to touch the summit of the knob M, was introduced into a Coulomb's torsion-balance, and found to be charged with a quantity of electricity represented by 250° of torsion. When the second apparatus was precisely similar to the first, it was found that, on contact of the two knobs, the charge divided itself equally, and the carrier-ball, if applied to either knob, took a charge represented very nearly by 125°.

The conditions were then changed in the following way. The first jar still containing air, the interval between the two conductors in the second was filled with shellac. It was then found that the air-jar, being charged to 290°, was reduced, by contact of its knob with that of the shellac-jar, to 114°, thus losing 176°. If no allowance be made for dissipation, the capacities of the air-jar and shellac-jar would

therefore be as 114 : 176, or as 1 : 1·54, and the specific inductive capacity of shellac would be 1·54.

626. Polarization of the Dielectric.—As the interposed non-conductor, or dielectric, modifies the mutual action of the two electricities which it separates, and does not play the mere passive part which was attributed to it before Faraday's experiments, it is natural to conclude that the dielectric must itself experience a peculiar modification. According to Faraday, this modification consists in a polarization of its particles, which act inductively upon each other along the lines of force, and have each a positive and a negative side, the positive side of each facing the negative side of the next. This polarization is capable of being sustained for a great length of time in good non-conductors; but in good conductors it instantly leads to discharge between successive particles, and the opposite electricities appear only at the two surfaces.

The polarization of dielectrics is clearly shown in the following experiment. In a glass vessel (Fig. 388) is placed oil of turpentine,

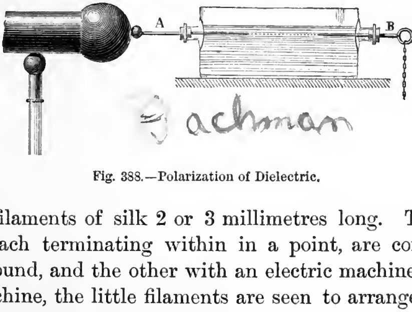

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Fig. 388.—Polarization of Dielectric.

containing filaments of silk 2 or 3 millimetres long. Two metallic rods, A, B, each terminating within in a point, are connected, one with the ground, and the other with an electric machine. On working the machine, the little filaments are seen to arrange themselves in a line between the points, and, on endeavouring to break the line with a glass rod, it will be found that they return to this position with considerable pertinacity. On stopping the machine, they immediately fall to the bottom.

An experiment of Matteucci's demonstrates this polarization still more directly. A number of thin plates of mica are pressed strongly together between two metallic plates. One of the metallic plates is charged, while the other is connected with the ground; and, on removing the metallic plates by insulating handles, it is found that all the mica plates are polarized, the face turned towards the positive

metal plate being covered with positive electricity, and the other face with negative.

Dr. Kerr has recently shown that glass and other transparent insulators, when subjected to strong dielectric action, become for the time doubly-refracting, a property which is also producible in such substances as glass by longitudinal extension or compression. In some substances, including glass itself, the dielectric effect is identical with the effect of *compression* along the lines of force. In others it is identical with the effect of *extension* along these lines. Liquid as well as solid dielectrics are thus affected, the only difference being that in solids the effect takes about half a minute to attain its maximum, and dies away gradually when the electrical forces are removed; whereas in liquids, the full effect is attained instantaneously, and the disappearance is also instantaneous. The direction of vision, in the experiments, was at right angles to the lines of force; and the optical effect, per unit of thickness in this direction, was found to vary, in any given liquid, directly as the square of the electric force.

627. Limit to Thinness of Interposed Plate.—We have seen (§ 617) that the capacity of a condenser varies inversely as the distance between the collecting and the condensing plate. But if this distance is very small, the resistance of the interposed dielectric (which varies directly as its thickness) may be insufficient to prevent discharge, and it will not be practicable to establish a great difference of potential between the two plates. We may practically distinguish two sorts of condensers, one sort having a very thin dielectric and very great condensing power, but only capable of being charged to feeble[1] potential; the other having a dielectric thick enough to resist the highest tensions attainable by the electrical machine. The Leyden jar comes under the second category. The first includes the electrophorus (except in so far as its action is aided by the metallic sole), and the condenser of Volta's electroscope.

628. Condensers for Galvanic Electricity.—Condensers of very large surface are used for certain applications of galvanic electricity, especially in connection with telegraphy. They are constructed by arranging a number of sheets of tin-foil in a pile, with either thin

[1] *Strong* potential is potential differing very much from zero either positively or negatively. *Feeble* potential is potential not differing much from zero. *Tension* is measured by difference of potential; and when the earth is one of the terms of the comparison, tension becomes identical with potential.

mica or paper saturated with paraffin wax between them. The 1st, 3d, 5th, &c., sheets of tin-foil are connected together and correspond to one coating of a Leyden jar, and the 2d, 4th, 6th, &c., sheets are connected and correspond to the other coating. They are charged by connecting one of these coatings to one pole of a battery and the other coating to the other pole.

629. Volta's Condensing Electroscope.—This instrument, which has rendered very important services to the science of electricity, differs from the simple gold-leaf electroscope previously described (§ 565), in having at its top two metal plates, of which the lower one is connected with the gold-leaves, and is covered on its upper face with insulating varnish, while the upper is varnished on its lower face, and furnished with a glass handle. These two plates constitute the condenser. In using the instrument, one of the two plates (it matters not which) is charged by means of the body to be tested, while the other is connected with the earth. They thus receive opposite and sensibly equal charges. The upper plate is then lifted off, and the higher it is raised the wider do the gold-leaves diverge. The separation of the plates diminishes the capacity, and strengthens the potential of both, one becoming more strongly positive, and the other more strongly negative. This involves increase of potential energy, which is represented by the amount of work done against electrical attraction in separating the plates. No increase in quantity of electricity is produced by the separation; hence the instrument is chiefly serviceable in detecting the presence of electricity which is available in large quantity but at weak potential. The glass handle of the upper plate is by no means essential, as it is only necessary that the lower plate should be insulated. The charge may be given by induction; in which case one plate must be connected with the earth while the inducing body is held near it, and the other plate must be kept connected with the earth while the influencing body is withdrawn. The plates will then be left charged with opposite electricities, that

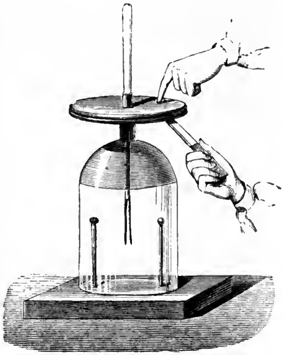


Fig. 389.—Condensing Electroscope.

which was more remote from the influencing body having acquired a charge similar to that of the body. For inductive charges, however, the condensing arrangement serves no useful purpose, beyond enabling the electroscope to retain its charge for a longer time, the effect finally obtained on separating the plates being no greater than would have been obtained by employing only the lower plate.

630. Leyden Battery.—The Leyden battery consists of a number of Leyden jars, placed in compartments of a box lined with tin-foil, which serves to establish good connection between their outer coat-

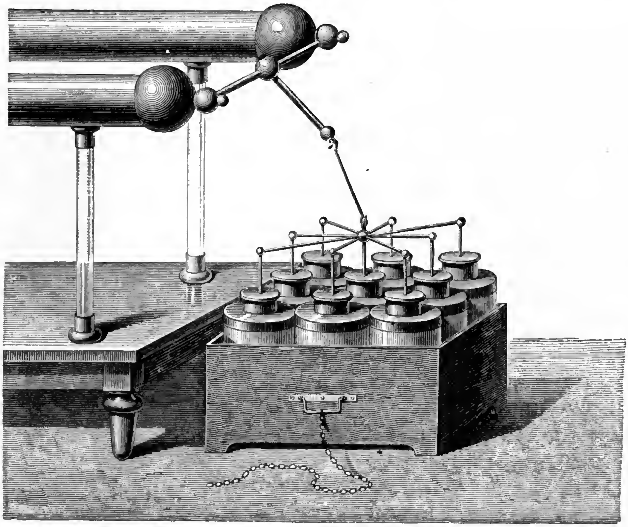


Fig. 390.—Battery of Leyden Jars.

ings, while their inner coatings are connected by brass rods. It is advisable that the outer coatings should have very free communication with the earth. For this purpose a metallic handle, which is in metallic communication with the lining of the box, should be connected, by means of a chain, with the gas or water pipes of the building.

The capacity of a Leyden battery is the sum of the capacities of the jars which compose it. The charge is given in the ordinary way,

by connecting the inner coatings with the conductor of the machine. In bad weather this is usually a very difficult operation, on account of the large quantity of electricity required for a full charge, and the large surface from which dissipation goes on.

Holtz's machine can be very advantageously employed for charging a battery, one of its poles being connected with the inner, and the other with the outer coatings. In dry weather it gives the charge with surprising quickness.

631. Lichtenberg's Figures.—An interesting experiment devised by

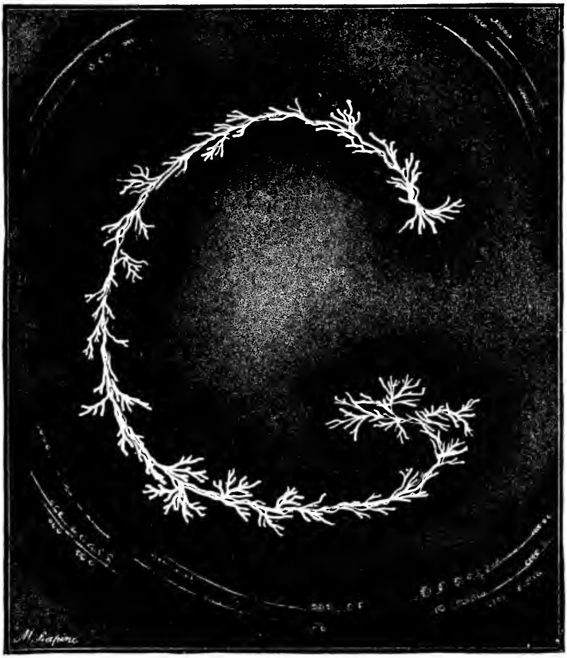


Fig. 391.—Lichtenberg's Figures.

Lichtenberg serves to illustrate the difference between the physical properties of positive and negative electricity.

A Leyden jar is charged, and the operator, holding it by the outer

coating, traces a design with the knob on a plate of shellac or vulcanite. He then places the jar on an insulating stand, to enable him to transfer his hold to the knob, and traces another pattern on the cake with the outer coating. A mixture of flowers of sulphur and red-lead, which has previously been well dried and shaken together, is then sprinkled over the cake. The sulphur, having become negatively electrified by friction with the red-lead, adheres to the pattern which was traced with positive electricity, while the red-lead adheres to the other. The yellow and red colours render the patterns very conspicuous. The particles of sulphur (represented by the inner pattern in Fig. 391) arrange themselves in branching lines, while the red-lead (shown in the outer pattern) forms circular spots; whence it would appear that positive electricity travels along the surface more easily than negative. A similar difference has already been pointed out between positive and negative brushes.

632. Charge by Cascade.—Instead of connecting all the inner coatings together, and all the outer coatings together, as in the Leyden battery, we may connect a number of jars in series. The inner coating of the first jar is to be connected with the prime conductor of the machine; and its outer coating, which must be insulated from the earth, is to be connected with the inner coating of the second jar. The outer coating of this is in like manner to be connected with the inner coating of the next, and so on to the last jar, the outer coating of which must be connected with the earth. When the machine is worked, a positive charge is given to the inner coating of the first, and a sensibly equal negative charge is induced upon its outer coating, this negative charge being drawn from the inner coating of the second, which accordingly acquires a positive charge sensibly equal to that given from the machine to the first jar. This reasoning can be extended through the whole chain. Hence if we denote by Q the charge given to the inner coating of the first jar, the inner coating of each jar in the series has a charge $+Q$, and the outer coating a charge $-Q$. If we further suppose all the jars to have the same capacity C, and if we denote the potentials of the inner coatings by $V_1, V_2, V_3, \ldots V_n$, we shall have

$$\frac{Q}{C} = V_1 - V_2 = V_2 - V_3 =, \text{\&c.}, = V^n - 0,$$

since the quotient of the charge of a jar by its capacity is equal to the difference of potential of the two coatings, and the potentials of the outer coatings are $V_2, V_3, \ldots V_n, 0$. By adding the n differ-

ences V_1-V_2, V_2-V_3 . . . V_n-0, we obtain V_1, which is accordingly equal to n times $\frac{Q}{C}$, and we have

$$\frac{Q}{C}=V_1-V_2=V_2-V_3=, \&c., =\frac{V_1}{n}.$$

If we compare the charges of these jars with the charge which the first jar would have received if its outer coating had been connected to earth in the ordinary way, the prime conductor being supposed to attain the same potential V_1 in both cases, we have

$$Q=\frac{1}{n}CV_1$$

for each jar in the series, whereas we should have had $Q'=CV_1$ for the single jar. The charge of each jar in the series is therefore $\frac{1}{n}$ of its ordinary charge.

As regards energy; for the single jar the energy would be $\frac{1}{2}Q'V_1=\frac{1}{2}CV_1^2$, while for any one jar in the series the energy would be

$$\tfrac{1}{2}Q(V_1-V_2)=\tfrac{1}{2}\frac{1}{n}CV_1\frac{V_1}{n}=\tfrac{1}{2}\frac{1}{n^2}CV_1^2,$$

which is $\frac{1}{n^2}$ of the energy of the single jar.

Jars thus arranged are said to be charged *by cascade*, the name being suggested by the successive falls of potential from jar to jar. They can either be discharged in succession by connecting the two coatings of each, or all together by connecting the inner coating of the first with the outer coating of the last. In the former case the energy of each spark is $\frac{1}{2}\frac{1}{n^2}CV_1^2$, as appears from the above calculation. In the latter case the energy of the single spark is $\frac{1}{2}\frac{1}{n}CV_1^2$.

CHAPTER XLVIII.

EFFECTS PRODUCED BY THE DISCHARGE OF CONDENSERS.

633. Discharge of Batteries.—The effects produced by the discharge of a Leyden jar or battery differ only in degree from those of an ordinary electric spark. The shock, which is smart even with a small jar, becomes formidable with a large jar, and still more with a battery of jars.

If a shock is to be given to a number of persons at once, they must form a chain by holding hands. The person at one end of the chain

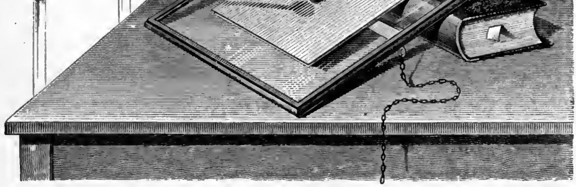


Fig. 392.—Coated Pane.

must place his hand on the outer coating of a charged jar, and the person at the other end must touch the knob. The shock will be felt by all at once, but somewhat less severely by those in the centre.

The *coated pane*, represented in Fig. 392, is simply a condenser, consisting of a pane of glass, coated on both sides, in its central portion, with tin-foil. Its lower coating is connected with the earth by

a chain, and a charge is given to its upper coating by the machine. When it is charged, if a person endeavours to take up a coin laid upon its upper face, he will experience a shock as soon as his hand comes near it, which will produce involuntary contraction of his arm, and prevent him from taking hold of the coin.

634. Heating of Metallic Threads.—The discharge of electricity through a conducting system produces elevation of temperature, the amount of heat generated being the equivalent of the potential energy which runs down in the discharge, and which is jointly proportional to quantity of electricity and difference of potential. The incandescence of a fine metallic thread can be easily produced by the discharge of a battery. The thread should be made to connect the knobs a b of an apparatus called a *universal discharger* (Fig. 393);

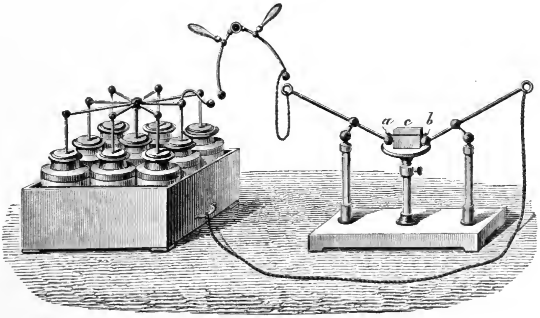


Fig. 393.—Universal Discharger.

these knobs being the extremities of two metallic arms supported on glass stems. One of the arms is connected with the external surface of the battery, and the other arm is then brought into connection with the internal surface by means of a discharger with glass handles. At the instant of the spark passing, the thread becomes red-hot, melts, burns, or volatilizes, leaving, in the latter cases, a coloured streak on a sheet of paper c placed behind it. When the thread is of gold, this streak is purple, and exactly resembles the marks left on walls when bell-pulls containing gilt thread are struck by lightning.

635. Electric Portrait.—The volatilization of gold is employed in producing what are called electric portraits. The outline of a por-

trait of Franklin is executed in a thin card by cutting away narrow strips. Two sheets of tin-foil are gummed to opposite edges of the card, which is then laid between a gold-leaf and another card. The whole is then placed in a press (Fig. 394); the tin-foil being allowed

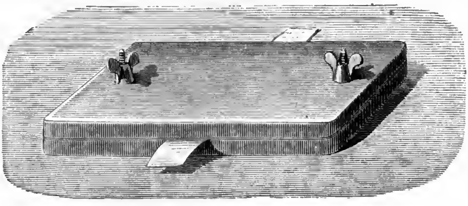


Fig. 394.—Press for Portrait.

to protrude, and strong pressure is applied. The press is placed on the table of the universal discharger, and the two knobs of the latter are connected with the two sheets of tin-foil. The discharge is then passed, the gold is volatilized, and the vapour, passing through the slits to the white card at the back, leaves purple traces which reproduce the design.

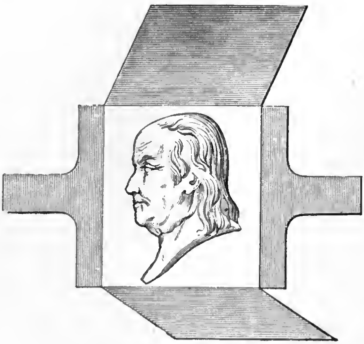


Fig. 395.—Arrangement for Portrait.

636. Velocity of Electricity.— Soon after the invention of the Leyden jar, various attempts were made to determine the velocity with which the discharge travels through a conductor connecting the two coatings. Watson, about 1748, took two iron wires, each more than a mile long, which he arranged on insulating supports in such a way that all four ends were near together. He held one end of each wire in his hands, while the other ends were connected with the two coatings of a charged jar. Although the electricity had more than a mile to travel along each wire before it could reach his hands, he could never detect any interval of time between the passage of the spark

from the knob of the jar and the shock which he felt. The velocity was in fact far too great to be thus measured.

Wheatstone, about 1836, investigated the subject with the aid of the revolving mirror of which we have spoken above (§ 591). He connected the two coatings of a Leyden jar by means of a conductor which had breaks in three places, thus giving rise to three sparks. When the sparks were taken in front of the revolving mirror, the positions of the images indicated a retardation of the middle spark, as compared with the other two, which were taken near the two coatings of the jar, and were strictly simultaneous. The middle break was separated from each of the other two by a quarter of a mile of copper wire. He calculated that the retardation of the middle spark was $\frac{1}{1,152,000}$ of a second, which was therefore the time occupied in travelling through a quarter of mile of copper wire. This is at the rate of 288,000 miles per second, a greater velocity than that of light, which is only about 186,000 miles per second.

Since the introduction of electric telegraphs, several observations have been taken on the time required for the transmission of a signal. For instance, trials in Queenstown harbour, in July, 1856, when the two portions of the first Atlantic cable, on board the *Agamemnon* and *Niagara*, were for the first time joined into one conductor, 2500 miles long, gave about $1\frac{3}{4}$ seconds as the time of transmission of a signal from induction coils, corresponding to a velocity of only 1400 miles per second. In 1858, before again proceeding to sea, a quicker and more sensitive receiving instrument—Thomson's mirror galvanometer—gave a sensible indication of rising current at one end of 3000 miles of cable about a second after the application of a Daniell's battery at the other.

It seems to be fully established by experiment that electricity has no definite velocity, and that its apparent velocity depends upon various circumstances, being greater through a short than through a long line, greater (in a long line) with the greater intensity and suddenness of the source, greater with a copper than with an iron wire, and much greater in a wire suspended in air on poles than in one surrounded by gutta-percha and iron sheathing, and buried under ground or under water. In a long submarine line, a short sharp signal sent in at one end, comes out at the other as a signal gradually increasing from nothing to a maximum, and then gradually dying away.

637. Unit-jar.—For quantitative experiments on the effects of discharge, Lane's *unit-jar* has frequently been employed. One of its forms is represented in Fig. 396. It consists of a very small Leyden phial, having two knobs a, b, one connected with each coating, the distance between them being adjustable by means of a sliding rod. To measure the charge given to a jar or battery, the latter is placed upon an insulating support, its inner coating is connected with the conductor of the machine, and its outer coating is connected with the inner coating of the unit-jar. The outer coating of the unit-jar must be in connection with the ground. When the machine is worked, sparks pass between a and b, each spark being produced by the escape of a definite quantity of electricity from the outer coating of the battery, and indicating the addition of a definite amount to the charge of the inner coating. The charge is measured by counting the sparks.

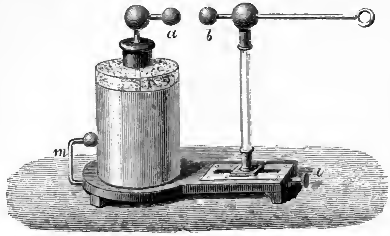


Fig. 396.—Unit-jar.

Snow Harris modified the arrangement by insulating the unit-jar instead of the battery. One coating of his unit-jar is connected with the battery, and the other with the conductor of the machine. The battery thus receives its charge through the unit-jar[1] by a succession of discharges between the knobs a, b, each representing a definite quantity of electricity.

Both arrangements, as far as their measuring power is concerned, depend upon the assumption that discharge between two given conductors, in a given relative position, involves the transfer of a definite quantity of electricity. This assumption implies a constant condition of the atmosphere. It may be nearly fulfilled during a short interval of time in one day, but is not true from one day to another. Moreover, it is to be remembered that, as dissipation is continually going on, the actual charge in the battery at any time is less than the measured charge which it has received.

[1] Lane's arrangement might have been described by saying that the *outer coating* of the battery receives its negative charge from the earth through the unit-jar.

638. Mechanical Effects.—The effects of discharge through bad conductors are illustrated by several well-known experiments.

1. *Puncture of card.* A card is placed (Fig. 397) between two points connected with two conductors with are insulated from one another by means of a glass stem. The lower conductor having been connected with the outer coating of a Leyden jar which is held in the hand, the knob of the jar is brought near the upper conductor. A spark passes, and another spark at the same instant passes between the two points, and punctures the card. In performing this

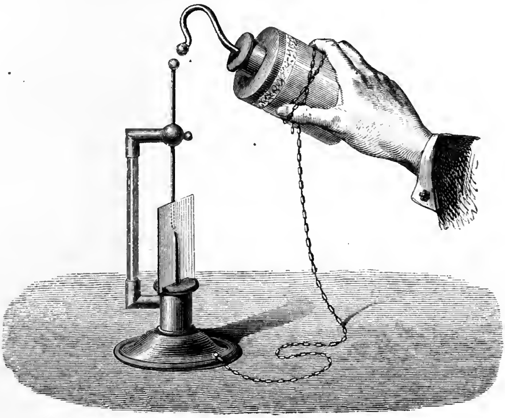


Fig. 397.—Puncture of Card.

experiment it is observed that, if the points are not opposite each other, the perforation is close to the negative point. This want of symmetry appears to be due to the properties of the air. When arrangements are made for exhausting the air, it is found that, as the density of the air is diminished, the perforation takes place nearer to the centre.

The piercing of a card can very easily be effected by Holtz's machine. Its two conductors are connected with the two coatings of a small Leyden jar. The discharges between the poles will then consist of powerful detonating sparks in rapid succession; and if a sheet of paper or card be interposed, every spark will puncture a minute hole in it.

2. *Perforation of Glass.* To effect the perforation of glass, a pane

of glass is supported on one end of a glass cylinder in whose axis there is a metallic rod terminating in a point which just touches the pane. Another pointed rod exactly over this, and insulated from it, is lowered until it touches the upper face of the pane. A powerful spark from a Leyden jar or battery is passed between the two points, and, if the experiment succeeds, a hole is produced by pulverization of the glass.

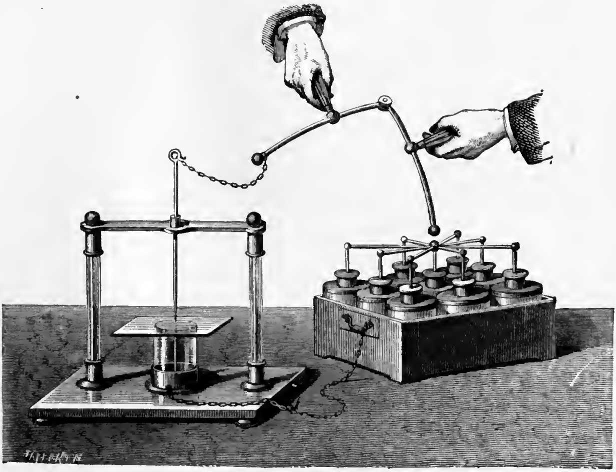


Fig. 398.—Puncture of Glass.

The experiment sometimes fails, by discharge taking place round the edge of the glass instead of through its substance. To prevent this, a drop of oil is placed on the upper face of the plane at the point where the hole is to be made; but this precaution does not always insure success, and, when the experiment has once failed, it is useless to try it again with the same piece of glass, for the electricity is sure to follow in the course which the first discharge has marked out for it.

639. Explosion of Mines.—If a strongly charged Leyden jar be discharged by means of a jointed discharger which has one of its knobs covered with gun-cotton, when the spark passes between the jar and this knob, the gun-cotton will be inflamed. Ordinary

cotton mixed with powdered resin can be kindled in the same way.

A similar arrangement is often used for exploding mines. A fuse is employed containing two wires embedded in gutta percha, but with their ends unprotected and near together. One of these wires is

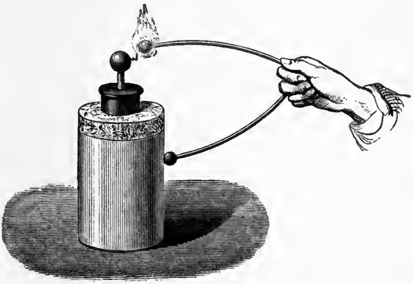


Fig. 399.—Gun-cotton Fired.

connected with the outer coating of a condenser, and the other is brought into communication with the inner coating. The discharge is thus made to pass between the ends within the fuse, and to ignite a very inflammable compound by which they are surrounded. Sometimes one of the wires, instead of being connected with the outer coating, is connected with the earth by means of a buried wire.

CHAPTER XLIX.

ELECTROMETERS.

640. Object of Electrometers.—Electrometers are instruments for the measurement of differences of electrical potential. The gold-leaf electroscope, the straw-electroscope, and other instruments of the same type, afford rough indications of the difference of potential between the diverging bodies and the air of the apartment, and more measurable indications are given by the electrometers of Peltier and Dellmann; but none of these instruments are at all comparable in precision to the various electrometers which have been invented from time to time by Sir Wm. Thomson.

641. Attracted-disc Electrometers, or Trap-door Electrometers.—We shall first describe what Sir Wm. Thomson calls "Attracted-disc Electrometers." These instruments, one of which is represented in Figs. 400, 401, contain two parallel discs of brass g, h, with an aperture in the centre of one of them, nearly filled up by a light trap-door of aluminium f, which is supported in such a way as to admit of its electrical attraction towards the other disc being resisted by a mechanical force which can be varied at pleasure. The trap-door and the perforated plate surrounding it must have their faces as nearly as possible in one plane when the observation is taken, and, as they are electrically connected, they may then be regarded as forming *one disc of which a small central area is movable.* There is always attraction between the two parallel discs, except when they are at the same potential.

Let their potentials be denoted by V and V′, the electrical densities on their faces by ρ and ρ', and their mutual distance by D. We have seen (§ 617) that, in such circumstances, ρ and ρ' are constant (except near the edges of the discs), opposite in sign, and equal, and that the intensity of force in the space between them is everywhere

the same, and equal at once to $\frac{V-V'}{D}$ and to $4\pi\rho$. This force is jointly due to attraction by one plate and repulsion by the other, each of these having the intensity $2\pi\rho$, or half the total intensity.

Let A denote the area of the trap-door. The quantity of electricity upon it will be ρA, and the force of attraction which this experiences will be $\rho A \times 2\pi\rho = 2\pi\rho^2 A$, which we shall denote by F. Then from the equations

$$F = 2\pi\rho^2 A \quad , \quad \frac{V-V'}{D} = 4\pi\rho, \qquad (1)$$

we find, by eliminating ρ,

$$F = \frac{A}{8\pi}\left(\frac{V-V'}{D}\right)^2, \text{ or } V-V' = \pm D\sqrt{\frac{8\pi F}{A}}. \qquad (2)$$

642. Absolute Electrometer.—In the *absolute electrometer*, which somewhat resembles Fig. 401 turned upside down, the force of electrical attraction on the trap-door is measured by direct comparison with the gravitating force of known weights. This is done by first observing what weights must be placed on the trap-door to bring it into position when no electrical force acts (the plates being electrically connected), and by then removing the weights, allowing electrical force to act, and adjusting the plates at such a distance from one another, by the aid of a micrometer screw, that the trap-door shall again be brought into position. Then, in equation (2), F, A, and D are known, and the difference of potentials $V-V'$ can be determined. In the absolute electrometer, the perforated disc h is uppermost, so that the direction of electrical attraction on the trap-door is similar to the direction of the gravitating force of the weights. The reverse arrangement is usually adopted in the portable electrometer, which we shall next describe. In both instruments, the trap-door constitutes one end of a very light lever $f\,i\,l$ of aluminium, balanced on a horizontal axis.

643. Portable Electrometer.—In the *portable electrometer* (Figs. 400, 401) this axis passes very accurately through the centre of gravity of the lever, the suspension being effected by means of a fine platinum wire $w\,w$ tightly stretched, which is secured at its centre to the lever in such a manner that, when the trap-door comes into position, the wire is under torsion tending to draw back the disc from the attracting plate g. This torsion (except in so far as it is affected by causes of error such as temperature and gradual loss of elasticity) is always the same when the disc is in position, and as it

is to be balanced in every observation by electrical attraction, the latter must also be always the same; that is to say, the quantity F in equations (2) is constant for all observations with the same instrument; whence it is obvious that $V-V'$ is directly proportional to D, the distance between the plates. The observation for difference of potential therefore consists in altering this distance until the trap-door comes into position. This is done by turning the micrometer

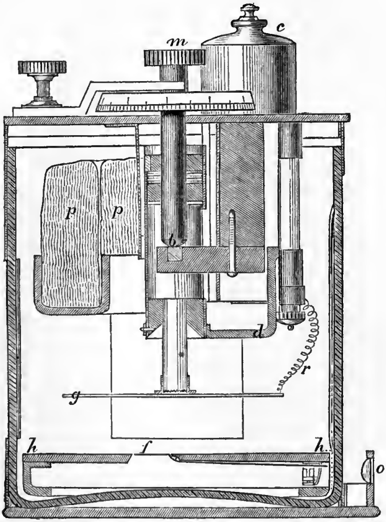


Fig. 400.—Portable Electrometer.

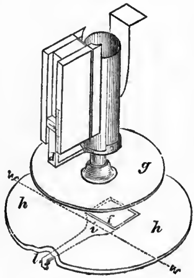


Fig. 401.—Parallel Discs.

screw, by means of the milled head *m*. The divided circle of the micrometer indicates the amount of turning for small distances, and whole revolutions are read off on the vertical scale traversed by the index carried by the arm *d*. The correct position is very accurately identified by means of two sights, one of them being attached to a fixed portion of the instrument, and the other to one end *l* of the lever. One of these sights moves up and down close in front of the other, and they are viewed through a lens *o* in front of both. This arrangement is also adopted in the absolute electrometer.

One of the two parallel plates h is connected with the inner coating of a Leyden jar,[1] which, being kept dry within by means of pumice p wetted with sulphuric acid, retains a sufficient charge for some weeks. The other plate g is in communication, by means of the spiral wire r, with the insulated umbrella c, which can be connected with any external conductor; and, in order to determine the

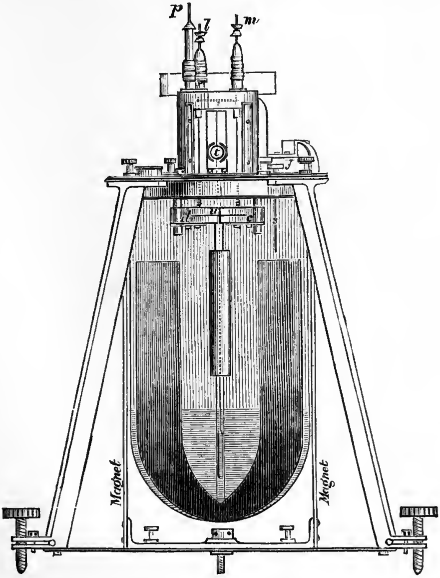


Fig. 402.—Quadrant Electrometer.

potential of any conductor which we wish to examine, two observations are taken, one of them giving the difference of potential between this conductor and the Leyden jar, and the other the difference between the earth and the jar. We thus obtain, by subtrac-

[1] The use of the Leyden jar is to give constancy of potential. Its capacity is so much greater than that of the disc with which it is connected that the electricity which enters or leaves the latter in consequence of the inductive action of the other disc is no sensible fraction of the whole charge of the jar, and produces no sensible change in its potential. Its great capacity in comparison with the extent of surface exposed likewise tends to prevent rapid loss of potential by dissipation of charge.

tion, the difference of potential between the conductor in question and the earth.

644. Quadrant Electrometer.—The most sensitive instrument yet invented for the measurement of electrical potential is the *quadrant electrometer*, which is represented in front view in Fig. 402, some of its principal parts being shown on a larger scale in Figs. 403, 404.

In this instrument, the part whose movements give the indications is a thin flat piece of aluminium u, narrow in the middle and broader towards the ends, but with all corners rounded off. This piece, which is called the *needle*, and is represented by the dotted line in Fig. 403, is inclosed almost completely in what may be described as a shallow cylindrical box of brass, cut into four quadrants, c, d, c', d'. These parts are shown in plan in Fig. 403, and in front view in Fig. 402. The needle u is attached to a stiff platinum wire, which is supported by a silk fibre hanging vertically. The same wire carries a small concave mirror t (Fig. 402) for reflecting the light from an illuminated vertical slit. An image of the slit is thus formed at the distance of about a yard, and is received upon a paper scale of equal parts, by reference to which the movements of the image can be measured. The movements of the image depend upon the movements of the mirror, which are precisely the same as those of the needle. We have now to explain how the movements of the needle are produced.

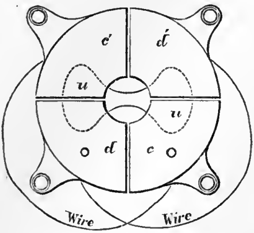


Fig. 403.—Needle and Quadrants.

One pair of opposite quadrants $c\,c'$ are connected with each other, and with a stiff wire l projecting above the case of the instrument. The other quadrants $d\,d'$ are in like manner connected with the other projecting wire m. The projecting parts $l\,m$ are called the *chief electrodes*, and are to be connected respectively with the two conductors whose difference of potential is required, one of which is usually the earth. Suppose the needle to have a positive charge of its own, then if the potential of c and c' be higher (algebraically) than that of d and d', one end of the needle will experience a force urging it from c to d, and the other end will experience a force urging it from c' to d'. These two forces constitute a couple tending to turn

the needle about a vertical axis. If the potential of c and c' be lower than that of d and d', the couple will be in the opposite direction. To prevent the needle from deviating too far under the action of this couple, and to give it a definite position when there is no electrical couple acting upon it, a small light magnet is attached to the back of the mirror, and by means of controlling magnets outside the case the earth's magnetism is overpowered, so that, whatever position be chosen for the instrument, the needle can be made to assume the proper zero position. In some instruments recently constructed, the magnets are dispensed with, and a bifilar suspension is substituted for the single silk fibre. The permanent electrification of the needle is attained by connecting it, by means of a descending platinum wire, with a quantity of strong sulphuric acid, which occupies the lower part of the containing glass jar. The acid, being an excellent conductor, serves as the inner coating of a Leyden jar, the outside of the glass opposite to it being coated with tin-foil, and connected with the earth. The acid at the same time serves the purpose of keeping the interior of the apparatus very dry. The charge is given to the jar through the *charging electrode* p, which can be thrown into or out of connection at pleasure. As the sensibility of the instrument increases with the potential of the jar, a *gauge* and *replenisher* are provided for keeping this potential constant. The *gauge* is simply an "attracted-disc electrometer," in which the distance between the parallel discs is never altered, so that the aluminium square only comes into position when the potential of one of the discs, which is connected with the acid in the jar, differs by a certain definite amount from the potential of the other, which is connected with the earth. A glance at the gauge shows, at any moment, whether the potential of the jar has the normal strength. If it has fallen below this point, the *replenisher* is employed to increase the charge.

This apparatus, which is separately represented, dissected, in Fig. 404, and is for simplicity omitted in Fig. 402, consists of a vertical stem of ebonite s, which can be rapidly twirled with the finger by means of a milled head y, and which carries two metal wings or *carriers*, b, b, insulated from each other. In one part of their revolution, these come in contact with two light steel springs ff, which simply serve to connect them for the instant with each other. In another part of their revolution, they come in contact with two other springs $e\,e$, connected respectively with the acid of the jar and with the earth. The first of these contacts takes place just before

the wings emerge from the shelter of the larger metallic sectors or *inductors a a*, of which one is connected with the acid, and the other with the earth. Suppose the acid to have a positive charge. Then, at the instant of contact, an inductive movement of electricity takes place, producing an accumulation of negative electricity in the carrier which is next the positive inductor, and an accumulation of positive in the other. The next contacts are effected when the carrier which has thus acquired a positive charge is well under cover of the positive inductor, to which accordingly it gives up its electricity; for, being in great part surrounded by this inductor, and being connected with it by the spring, the carrier may be regarded as forming a portion of the interior of a concave conductor, and the electricity accordingly passes from it to the external surface, that is to the inductor, and to the acid connected with it, which forms the lining of the jar. The negative electricity on the other carrier is, in like manner, given off to the other inductor, and so to the earth.

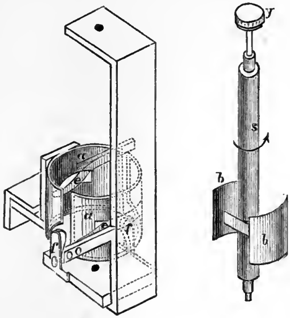


Fig. 404.—Replenisher.

The jar thus receives an addition to its charge once in every half-revolution of the replenisher; and, as these increments are very small, it is easy to regulate the charge so that the gauge shall indicate exactly the normal potential. If the charge is too strong, it can be diminished by turning the replenisher in the reverse direction.

NOTE ON THE ENERGY OF A SYSTEM OF CHARGED CONDUCTORS, WITH APPLICATION TO THOMSON'S QUADRANT ELECTROMETER.

(1.) By the energy of a system of charged conductors is meant the work which must have been spent in charging them, or, what is the same thing, the energy which will run down when the conductors are connected with the earth. We shall investigate its amount in terms of the charges Q_1 Q_2 &c., of the conductors, and their potentials V_1 V_2 &c., these latter being supposed to depend only on the charges of the system itself.

Let the conductors be charged gradually all at the same time, and let their charges at any time be xQ_1, xQ_2 &c., the value of x being the same for all the conductors. The potentials at the same time will be xV_1, xV_2

&c. By § 606, the work required to bring the small quantity of electricity $Q_1\,dx$ from the earth to the conductor of potential xV_1 is $xV_1\,Q_1\,dx$; thus, when x receives the small increase dx, the whole addition of energy to the system is

$$(V_1 Q_1 + V_2 Q_2 + \&c.)\; x\,dx.$$

If this operation is repeated time after time, beginning with $x = 0$, and ending with $x = 1$, the conductors will begin with being uncharged, and will end by having the given charges. Since the integral of $x\,dx$ between these limits is $\frac{1}{2}$, *the whole energy acquired by the system is* $\frac{1}{2}(V_1 Q_1 + V_2 Q_2 +$ &c.), which may be written $\frac{1}{2}\Sigma V Q$.

(2.) Hence when any small changes dQ_1, dQ_2, &c., are made in the charges, and any small changes dV_1, dV_2, &c., in the potentials, either with or without displacement of the conductors, the increase of energy is $\frac{1}{2}\Sigma(V dQ + Q dV)$.

(3.) If the conductors are *stationary*, another simple expression can be found for the increase of energy; for the work required to bring the electricity dQ_1 to the conductor of potential V_1 is $V_1\,dQ_1$; thus the whole increase of energy is $\Sigma V\,d\,Q$; and by comparing this with the expression for the same thing in (2.) we see that a third expression for the increase of energy will be $\Sigma Q\,d\,V$.

(4.) If the conductors are insulated, so that their *charges remain constant*, the increase of energy when they are displaced will be the difference between the initial energy $\frac{1}{2}\Sigma Q V$ and the final energy $\frac{1}{2}\Sigma Q V'$, that is, will be $\frac{1}{2}\Sigma Q(V' - V)$, where V' denotes the final potential of the conductor whose initial potential is V. If the charges are small the increase of energy will be $\frac{1}{2}\Sigma Q\,d\,V$. This, it will be noticed, is exactly half the increase in (3.), the changes of potential being supposed the same in both cases.

When insulated charged conductors are allowed to move under the influence of their own mutual forces, these forces will do positive work, and the system will lose electrical energy of the same amount. On the other hand, if external forces move the conductors in opposition to their mutual forces, there will be a gain of electrical energy equal to the work done by external forces against the forces of the system. These consequences follow immediately from the principle of the conservation of energy.

(5.) If the conductors while displaced are kept *at constant potentials*, their charges must change, and we cannot make the same direct application of the principle of conservation of energy which we have made above, unless we include in our reasonings the external sources from which electricity comes or to which it goes in making these alterations in the charges. We can, however, arrive at the relation between the change of energy in the system and the work done in the following way.

Divide the whole displacement into a series of small steps. In each step let the conductors be insulated, so that the potentials will change slightly, and then let the potentials be restored to their original values before the next step. The forces between the conductors will thus be sensibly the same as if the potentials were absolutely constant, and the work done by these forces will be the same.

In any one of the steps, the increase of energy, by (4.), is $\frac{1}{2}\Sigma Q\,dV$, and in the restoration of the potentials to what they were at the beginning of this step the increase of energy, by (3.), is $-\Sigma Q\,dV$, the minus sign being rendered necessary by the fact that the change from $V+dV$ back to V is $-dV$.

In the two operations combined the whole increase of energy is $-\frac{1}{2}\Sigma Q\,dV$, and the mechanical work done by the forces of the system is, by (4.), equal to the loss of energy in the displacement which constitutes the first operation, that is to $-\frac{1}{2}\Sigma Q\,dV$ also. Hence in each step combined with its following restoration of potential, the change of energy is the same both in amount and in sign as the work which the forces of the system do in the movements. As this equality holds through all the steps, it holds for the complete result; that is, the *gain of energy* in a system of conductors which are *displaced at constant potentials* is equal to the *work which the forces of the system do* in the displacement. In any system cut off from external supplies of energy the work done is equal to the energy lost, but here it is equal to the energy gained. Hence the external sources which supply the electricity for keeping the conductors at constant potentials furnish an amount of energy double of the work done by the forces of the system. On the other hand, if the conductors are moved in opposition to the forces of the system, the external sources will draw energy from the system to double the amount of the work done against the forces of the system.

(6.) In Thomson's quadrant electrometer, let V denote the potential of the needle and sulphuric acid, V_1 the potential of one pair of quadrants which we will call the first pair, and V_2 the potential of the other pair. The needle and quadrants form two condensers, the inner coatings of both being at the same potential V, and the outer coatings at the respective potentials V_1 and V_2. When the needle turns through an angle θ from the first pair of quadrants towards the second, the capacity of the first condenser is diminished by a quantity proportional to θ, say $c\theta$, and the capacity of the second condenser is increased by the same amount. Hence, supposing V to be higher than V_1, and V_1 than V_2, the charge of the needle is in one part diminished by $c\theta(V-V_1)$, and in another part increased by $c\theta(V-V_2)$, making a total increase of $c\theta(V_1-V_2)$.

The charge of the first pair of quadrants, being opposite in sign to that of the included portion of the needle, is increased algebraically by $c\theta(V-V_1)$, and that of the second pair is diminished by $c\theta(V-V_2)$.

The total increase in the expression $\frac{1}{2}(VQ + V_1Q_1 + V_2Q_2)$ for the energy of the system composed of the needle and quadrants is therefore

$$\begin{aligned}&\tfrac{1}{2}c\theta\left\{V(V_1 - V_2) + V_1(V - V_1) + V_2(V_2 - V)\right\}\\&= c\theta\left\{V(V_1 - V_2) - \tfrac{1}{2}(V_1^2 - V_2^2)\right\}\\&= c\theta(V_1 - V_2)\left(V - \frac{V_1 + V_2}{2}\right).\end{aligned}$$

This is the increase of energy produced by the displacement of the needle through the angle θ while the three potentials remain unchanged, and is equal, by (5.), to the work done by the electrical forces against the mechanical forces of the bifilar suspension. Dividing the work by the angle, we get the average working couple. This quotient

$$c(V_1 - V_2)\left(V - \frac{V_1 + V_2}{2}\right)$$

is independent of θ, and of the sensibility of the bifilar suspension. It is therefore the value of the working couple itself. It is balanced by the couple due to the suspension, which is proportional to θ. Hence the deflection θ is proportional to

$$(V_1 - V_2)\left(V - \frac{V_1 + V_2}{2}\right).$$

(7.) In the ordinary use of the instrument, V is very large compared with V_1 and V_2. Hence θ is sensibly proportional to $V_1 - V_2$.

(8.) If the needle is connected with the first pair of quadrants, V_1 may be substituted for V, and the deflection is proportional to $(V_1 - V_2)^2$. The direction of the deflection will be from the first pair towards the second, whether $V_1 - V_2$ be positive or negative. Joubert has taken advantage of this circumstance to use the instrument for measuring the difference of potential between the two terminals of an alternate-current dynamo. He connects these terminals with the electrodes of the quadrant electrometer, having first discharged the needle and sulphuric acid and connected them with one pair of quadrants. The difference of potential is reversed in sign, as well as changed in amount, some hundreds of times per second, and the needle gives a steady deflection which is proportional to the mean square of the difference of potential.

CHAPTER L.

ATMOSPHERIC ELECTRICITY.

646. Resemblance of Lightning to the Electric Spark.—The resemblance of the effects of lightning to those of the electric spark struck the minds of many of the early electricians. Lightning, in fact, ruptures and scatters non-conducting substances, inflaming those which are combustible; heats, reddens, melts, and volatilizes metals; and gives shocks, more or less severe, and frequently fatal, to men and animals; all of these being precisely the effects of the electric spark with merely a difference of intensity. We may add that lightning leaves behind it a characteristic odour precisely similar to that which is observed near an electrical machine when it is working, and which we now know to be due to the presence of ozone. Moreover, the form of the spark, its brilliancy, and the detonation which attends it, all remind one forcibly of lightning.

To Franklin, however, belongs the credit of putting the identity of the two phenomena beyond all question, and proving experimentally that the clouds in a thunder-storm are charged with electricity. This he did by sending up a kite, armed with an iron point with which the hempen string of the kite was connected. To the lower end of the string a key was fastened, and to this again was attached a silk ribbon intended to insulate the kite and string from the hand of the person holding it. Having sent up the kite on the approach of a storm, he waited in vain for some time even after a heavy cloud had passed directly over the kite. At length the fibres of the string began to bristle, and he was able to draw a strong spark by presenting his knuckle to the key. A shower now fell, and, by wetting the string, improved its conducting power, the silk ribbon being still kept dry by standing under a shed. Sparks in rapid succession were drawn from the key, a Leyden jar was charged by it, and a shock given.

Shortly before this occurrence, Dalibard, acting upon a published suggestion of Franklin, had erected a pointed iron rod on the top of a house near Paris. The rod was insulated from the earth, and could be connected with various electrical apparatus. A thunder-storm having occurred, a great number of sparks, some of them of great power, were drawn from the lower end of the rod.

These experiments were repeated in various places, and Richmann of St. Petersburg, while conducting an investigation with an apparatus somewhat resembling that of Dalibard, received a spark which killed him on the spot.

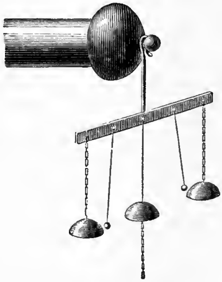


Fig. 405.—Electric Chimes.

647. Electric Chimes.—Franklin devised an apparatus for giving warning when the insulated rod is charged with electricity. It consists (Fig. 405) of a metal bar, carrying three bells with two clappers between them. The two extreme bells are hung from the bar by metallic chains. The middle one is hung by a silk thread, and connected with the ground. The clappers are also hung by silk threads. When the bar is electrified, the clappers are first attracted by the two extreme bells, and then repelled to the middle bell, through which they discharge themselves, to be again attracted and repelled, thus keeping up a continual ringing as long as the bar remains electrified.

648. Duration of Lightning.—It appears that thunder-clouds must be regarded as charged masses of considerable conducting power. The discharges which produce lightning and thunder occur sometimes between two clouds, and sometimes between a cloud and the earth. The duration of the illumination produced by lightning is certainly less than the ten-thousandth of a second. This has been established by observing a rapidly rotating disc (Fig. 406) divided into sectors alternately black and white. If viewed by daylight, the disc appears of a uniform gray; and if lightning, occurring in the dark, renders the separate sectors visible, the duration of its light must be less than the time of revolving through the breadth of one sector. The experiment has been tried with a disc divided into 60 sectors, and making 180 revolutions per second, so that the time of turning through the

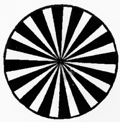


Fig. 406. Duration of Flash.

space occupied by one sector is $\frac{1}{60}$ of $\frac{1}{180}$ of a second, that is, $\frac{1}{10800}$. When the disc, turning with this velocity, is rendered visible by lightning, the observer sees black and white sectors with gray ones between them. For the black and white sectors to be seen sharply defined, without intermediate gray, it would be necessary that the illumination should be absolutely instantaneous.

649. Thunder.—Thunder frequently consists of a number of reports heard in succession. This can be explained by supposing that (as in the experiment of the spangled tube, § 594) discharge occurs at several places at once. The reports of these explosions will be heard in the order of their distance from the observer. If, for example, the lines of discharge form the zig-zag M N (Fig. 407), an observer at O will hear first the explosion at a, then, a little later, the five explosions at m, n, r, s, t; he will consequently observe an increase of loudness. When any considerable portion of the path of discharge is at a uniform distance from the observer, the simultaneous arrival of the disturbances propagated from all this portion will produce a specially loud burst of sound.

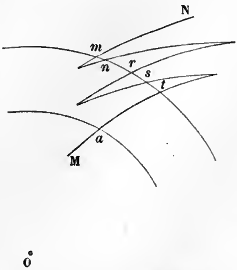


Fig. 407.—Simultaneous Explosions.

650. Shock by Influence.—Persons near whom a flash of lightning passes, frequently experience a severe shock by induction. This is analogous to the phenomenon, first observed by Galvani, that a skinned frog in the neighbourhood of an electrical machine, although dead, exhibits convulsive movements every time a spark is drawn from the conductor. In like manner, if Volta's pistol (§ 597) be placed on the wooden supports of an electrical machine, and its knob be connected with the ground by a chain, on drawing a spark from the machine, another spark will pass in the interior of the pistol, and fire it off.

651. Lightning-conductors.—Experience having shown that electricity travels in preference through the best conductors, it is easy to understand that, if a building be fitted with metallic rods terminating in the earth, lightning will travel through these instead of striking the building. But further, if these rods terminate above in a point, they may exercise a preventive influence by enabling the earth and clouds to exchange their opposite electricities in a gradual way,

just as the conductor of a machine is prevented from giving powerful sparks by presenting to it a sharp point connected with the earth.

While the electrical machine is working powerfully, and the quadrant electroscope shows a strong charge, let a pointed metallic rod be presented, as in Fig. 408; the pith-ball will immediately fall back to the vertical position, and it will be found impossible to draw a spark

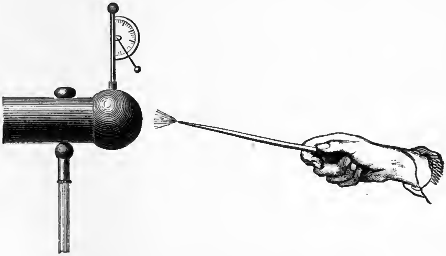


Fig. 408.—Conductor Discharged by presenting a Point.

from any part of the conductor. If the experiment is performed in the dark, the point will be seen to be tipped with light; and a similar appearance is sometimes observed on the tops of lightning-rods and of ships' masts. In the latter position it is known to sailors as *St. Elmo's fire.*

652. Construction of Lightning-conductors.—A badly constructed lightning-conductor may be a source of danger, instead of a protection. The following conditions should always be complied with:—

1. The connection with the ground should be continuous.

2. The conductor must be everywhere of so large a section that it will not be melted by lightning passing through it. The French Academy of Sciences recommend that the section for iron rods should be nowhere less than 2·25 centimetres, or $\frac{9}{10}$ of an inch.

3. The earth contact must be good. The conductor may be connected at its base with the iron pipes which supply the neighbourhood with water or gas; or it may terminate in the water of a well or pond. Failing these, it should be provided with branches traversing the soil in different directions and surrounded by coke, which is a good conductor.

4. At no part of its course above ground should it come near to the metal pipes which supply the house with water or gas, nor to any

large masses of metal in the house. All large masses of metal on the outside of the house, such as lead roofing, should be well connected with the conductor.

Fig. 409.—Lightning-conductor.

5. The extreme point should be sharp. A former commission of the Academy recommended a platinum point, which should be connected with the iron by welding. But as this construction is both difficult and expensive, later directions have been issued recommending a gilded copper cone, screwed on to the iron, as shown in Fig. 410, which is half the actual size. This form of termination is better than a needle point, because less liable to fusion.

The general arrangement is represented in Fig. 409. The rod has a diameter of 2 or 3 inches at its base, and gradually tapers upwards to the place where the point is screwed on. The descending portion b is connected with the base of this rod by the broad band ll'.

653. Ordinary Electricity of the Atmosphere.—The presence of electricity in the upper regions of the air is not confined to thunder-clouds, but can be detected at all times. In fine weather this electricity is almost invariably positive, but in showery or stormy weather negative electricity is as frequently met with as positive; and it is in such weather that the indications of electricity, whether positive or negative, are usually the strongest.

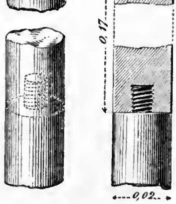


Fig. 410.—Gilded Copper Point.

654. Methods of obtaining Indications.—One of the early methods of observing atmospheric electricity consisted in shooting up an arrow, attached to a conducting thread, having at its lower end a ring, which was laid upon the

top of a gold leaf electroscope. As the arrow ascends higher, the leaves diverge more and more with electricity of the same sign as that overhead; and they remain divergent after the ring has been lifted off by the movement of the arrow.

Sometimes, instead of the arrow, a point on the top of the electroscope is employed to collect electricity from the air, as in Fig. 411. Both these methods are very uncertain in their action.

A better method of collecting electricity from the air was long ago devised by Volta, who employed for this purpose a burning match attached to the top of a rod connected with the gold-leaves or straws of his electroscope. If there is positive electricity overhead, its influence causes negative electricity to collect at the upper end of the rod, whence it passes off by convection in the products of combustion of the match, leaving the whole conducting system positively electrified. In like manner, if the electricity overhead be negative, the system will be left negatively electrified.

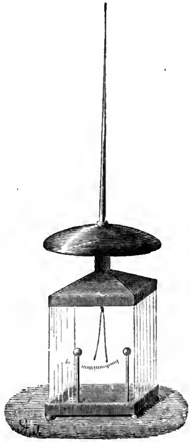


Fig. 411.—Early form of Electrometer.

Another method which, in the hands of Peltier, Quetelet, and Dellmann, has yielded good results, consists in first exposing, in an elevated position such as the top of a house, a conducting ball supported on an insulating stand, and, while exposed, connecting it with the earth; then insulating it, and examining the charge which it has acquired. This charge, being acquired from the earth by the inductive action of the electricity overhead, is opposite in sign to the inducing electricity.

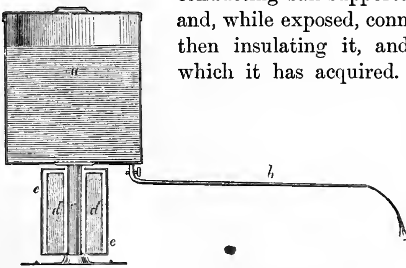


Fig. 412.—Water-dropping Collector.

Another method, which in principle resembles that of Volta, but is speedier in its action, has been introduced by Sir W. Thomson. It consists in allowing a fine stream of water to flow, from an in-

sulated metallic vessel, through a pipe, which projects through an open window or other aperture in the wall of a house, so that the nozzle from which the water flows is in the open air. The apparatus for this purpose, called the water-dropping collector, is represented in Fig. 412. *a* is a copper can, containing water, which can be discharged through the brass pipe *b* by turning a tap. The mode of insulation is worthy of notice. The can is supported on a glass stem *c*, which is surrounded, without contact, by a ring or rings of pumice *d d*, moistened with sulphuric acid. These are protected by an outer case of brass *e e*, having a hole in its top rather larger than the glass stem, the brass being separated from the moist pumice by an inner case of gutta percha. The acid needs renewal about once in two months.

In severe frost, burning matches can be used instead of water, and are found to give identical indications. Whether water or match be used, the principle of action[1] is that, as long as any difference of potential exists between the insulated conductor and the point of the air where the issuing stream (whether of water or smoke) ceases to be one continuous conductor, and begins to be a non-conductor or a succession of detached drops, so long will each drop or portion that detaches itself carry off either positive or negative electricity, and thus diminish the difference of potential. The time required to reduce the system to the potential which exists at the point above specified, is practically about half a minute with the water-jet, and from half a minute to a minute or more, according to the strength of the wind, with a match.

The water-dropper is the most convenient collecting apparatus when the observations are taken always in the same place. For

[1] The following quotation from an article by Sir W. Thomson puts the matter very clearly:—"If, now, we conceive an elevated conductor, first belonging to the earth, to become insulated, and to be made to throw off, and to continue throwing off, portions from an exposed part of its surface, this part of its surface will quickly be reduced to a state of no electrification, and the whole conductor will be brought to such a potential as will allow it to remain in electrical equilibrium in the air, with that portion of its surface neutral. In other words, the potential throughout the insulated conductor is brought to be the same as that of the particular equi-potential surface in the air, which passes through the point of it from which matter breaks away. A flame, or the heated gas passing from a burning match, does precisely this: the flame itself, or the highly heated gas close to the match, being a conductor which is constantly extending out, and gradually becoming a non-conductor. The drops [into which the jet from the water-dropper breaks] produce the same effects, with more pointed decision, and with more of dynamical energy to remove the rejected matter, with the electricity which it carries, from the neighbourhood of the fixed conductor."—*Nichol's Cyclopædia*, second edition, art. "Electricity, Atmospheric."

portable service, Sir Wm. Thomson employs blotting-paper, steeped in solution of nitrate of lead, dried, and rolled into matches. The portable electrometer carries a light brass rod or wire projecting upwards, to the top of which the matches can be fixed.

655. Interpretation of Indications.—We have seen that the collecting apparatus, whether armed with water-jet or burning match, is merely an arrangement for reducing an insulated conductor to the potential which exists at a particular point in the air. An electrometer will then show us the difference between this potential and that of any other given conductor, for example the earth. The earth offers so little resistance to the passage of electricity, that any temporary difference of potential which may exist between different parts of its surface, must be very slight in comparison with the differences of potential which exist between different points in the non-conducting atmosphere above it. As there is no possible method of determining absolute potential, since all electric phenomena would remain unchanged by an equal addition to the potentials of all points, it is convenient to assume, as the zero of potential, that of the most constant body to which we have access, namely the earth; and under the name earth we include trees, buildings, animals, and all other conductors in electrical communication with the soil.

Now we find that, as we proceed further from the earth's surface, whether upwards from a level part of it, or horizontally from a vertical part of it, such as an outer wall of a house, the potential of points in the air becomes more and more different from that of the earth, the difference being, in a broad sense, simply proportional to the distance. Hence we can infer[1] that there is electricity residing on the surface of the earth, the density of this electricity, at any moment, in the locality of observation, being measured by the difference of potential which we find to exist between the earth and a given point in the air near it. Observations of so-called atmospheric electricity[2] made in the manner we have described, are in fact simply

[1] By § 609, if ρ denote the quantity of electricity per unit area on an even part of the earth's surface, the force in the neighbouring air is $4\pi\rho$. This must be equal to the change of potential in going unit distance (§ 602). If potential increases positively, ρ is negative.

[2] No good electrical observations have yet been made in balloons, and very little is known regarding the distribution of electricity at different heights in the air. A method of gauging this distribution by balloon observations is suggested by the principles of § 607, which show that, when the lines of force are vertical, and the tubes of force consequently cylindrical, the difference of electrical force at different heights is proportional to the quantity of electricity which lies between them.

determinations of the quantity of electricity residing on the earth's surface at the place of observation. The results of observations so made are however amply sufficient to show that electricity residing in the atmosphere is really the main cause of the variations observed. A charged cloud or body of air induces electricity of the opposite kind to its own on the parts of the earth's surface over which it passes; and the variations which we find to occur in the electrical density at the parts of the surface where we observe, are so rapid and considerable, that no other cause but this seems at all adequate to account for them. We may therefore safely assume that the difference of potential which we find, in increasing our distance from the earth, is mainly due to electricity induced on the surface of the earth by opposite electricity in the air overhead.

As electrical density is greater on projecting parts of a surface than on those which are plane or concave, we shall obtain stronger indications on hills than in valleys, if our collecting apparatus be at the same distance from the ground in both cases. Under a tree, or in any position excluded from view of the sky, we shall obtain little or no effect.

656. Results of Observation.—The only regular series of observations taken with Sir Wm. Thomson's instruments which have yet been published,[1] consist of two years' continuous observations with self-recording apparatus at Kew Observatory, and two years' observations, at three stated times daily, and at other irregular times, at Windsor in Nova Scotia (lat. 45° N.). The electrometer used at Kew was an earlier form of the quadrant electrometer already described; and the autographic registration was effected by throwing the image of a bright point (a small hole with a lamp behind it) upon a sheet of photographic paper drawn upwards by clock-work, whereas the movements of the image, formed by means of the mirror attached to the needle, were horizontal. The curves thus obtained give very accurate information respecting the potential of the air at the point of observation, when of moderate strength; but fail to record it when of excessive strength, as the image on these occasions passed out of range. The Windsor observations were taken with the cage-electrometer, of which two forms were employed, one being much more sensitive than

[1] The observations at Windsor, N.S., and at Kew, are described in three papers by the editor of this work, *Proc. R. S.*, June 1863, January 1865, and *Trans. R. S.*, December 1867. Dellmann's observations at Kreuznach, which were taken with apparatus devised by himself, are described in *Phil. Mag.* June 1858. Quetelet's observations (taken with Peltier's apparatus) are described in his volume *Sur le Climat de la Belgique* (Brussels, 1849).

the other. The more sensitive form was usually employed. When the potential became inconveniently strong, the first step was to shorten the discharging pipe by screwing off some of its joints. This reduced the strength of potential in about the ratio of 3 : 1; but even this reduction was often not enough for the more sensitive instrument, and on such occasions the other (which was intended as a portable electrometer) was employed instead. As the ratio of the indications of the two instruments was known, a complete comparison of potentials in all weathers was thus obtained. The results are as follows:

Employing a unit in terms of which the average fine-weather potential for the year was $+4$, the potential was seldom so weak as 1, though on rare occasions it was for a few minutes as low as 0·1. In wet weather, especially with sudden heavy showers, the potential was often as strong as ± 20 to ± 30, and it was fully as strong during hail. With snow, the average strength was about the same as with heavy rain, but it was less variable, and the sign was almost always positive. Occasionally, with high wind accompanying snow, during very severe frost, it was from $+80$ to $+100$, or even higher. With fog, it was always positive, averaging about $+10$. In thunder-storms it frequently exceeded ± 100, and on a few occasions exceeded -200. There was usually a great predominance of negative potential in thunder-storms. Change of sign was a frequent accompaniment of a flash of lightning or a sudden downpour of rain. At all times, there was a remarkable absence of steadiness as compared with most meteorological phenomena, wind-pressure being the only element whose fluctuations are at all comparable, in magnitude and suddenness, with those of electrical potential. Even in fine weather, its variations during two or three minutes usually amount to as much as 20 per cent. In changeable and stormy weather they are much greater; and on some rare occasions it changes so much from second to second that, notwithstanding the mitigating effect of the collecting process, which eases off all sudden changes, the needle of the electrometer is kept in a continual state of agitation.

657. Annual and Diurnal Variations.—Observations everywhere[1] concur in showing that the average strength of potential is greater in winter than in summer; but the months of maxima and minima appear to differ considerably at different places. The chief maximum

[1] The remarks in this section express the results of observation at places all of which are in the north temperate zone.

occurs in one of the winter months, varying at different places from the beginning to the end of winter; and the chief minimum occurs everywhere in May or June. Both Kew and Windsor show distinctly two maxima in the year, but Brussels, and apparently Kreuznach, show only one. The ratio of the highest monthly average to the lowest is at Kew about 2·5, at Windsor 1·9, and at Kreuznach 2·0.

The Kew observations, being continuous, are specially adapted to throw light on the subject of diurnal variation. They distinctly indicate for each month two maxima, which in July occur at about 8 A.M. and 10 P.M., in January about 10 A.M. and 7 P.M., and in spring and autumn about 9 and 9. The result of the Brussels observations is about the same.

658. Causes of Atmospheric Electricity.—Various conjectures have been hazarded regarding the sources of atmospheric electricity; but little or no certain knowledge has yet been obtained on this subject. Evaporation has been put forward as a cause, but, as far as laboratory experiments show, whenever electricity has been generated in connection with evaporation, the real source has been friction, as in Armstrong's hydro-electric machine. The chemical processes involved in vegetation have also been adduced as causes, but without any sufficient evidence. It is perhaps not too much to say that the only natural agent which we know to be capable of electrifying the air is the friction of solid and liquid particles against the earth and against each other by wind. The excessively strong indications of electricity observed during snow accompanied by high wind, favour the idea that this may be an important source.

Without knowing the origin of atmospheric electricity, we may, however, give some explanation of the electrical phenomena which occur both in showers and in thunder-storms. Very dry air is an excellent non-conductor; very moist air has, on the other hand, considerable conducting power. When condensation takes place at several centres, a number of masses of non-conducting matter are transformed into conductors, and the electricity which was diffused through their substance passes to their surfaces. These separate conductors influence one another. If one of them is torn asunder while under influence, its two portions may be oppositely charged; and if rain falls from the under surface of a cloud which is under the influence of electricity above it, the rain which

falls may have an opposite charge to the portion which is left suspended.

Lord Rayleigh has found that drops of water which are slightly electrified have a tendency to coalesce, whereas unelectrified drops usually rebound after collision.[1] It is probable that electricity may in this way give rise to showers.

The coalescence of small drops to form large ones, though it increases the electrical density on the surfaces of the drops, does not increase the total quantity of electricity, and therefore (§ 611) cannot directly influence the observed potential.

Thunder-storms and other powerful manifestations of atmospheric electricity seem to be accompaniments of very sudden and complete condensation which gives unusually free scope to the causes of irregular distribution just indicated.

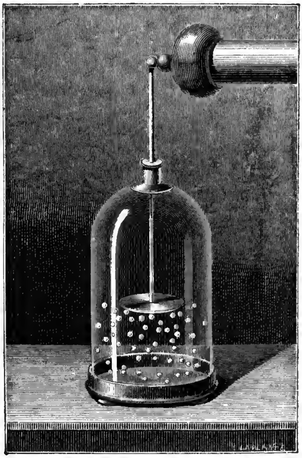


Fig. 413.—Electric Hail.

659. Hail.—Hail has sometimes been ascribed to an electrical origin, and a singular theory was devised by Volta to account for the supposed fact that hailstones are sustained in the air. He imagined that two layers of cloud, one above the other, charged with opposite electricities, kept the hailstones continually moving up and down by alternate attraction and repulsion. An experiment called *electric hail* is sometimes employed to illustrate this idea. Two metallic plates are employed (Fig. 413), the lower one connected with the earth, and the upper one with the conductor of the electrical machine; and pith-balls are placed between them. As the machine is turned, the balls fly rapidly backwards and forwards from one plate to the other.

[1] The observation was made upon jets discharged from a nozzle directed upwards, and it was found that connecting the discharging vessel with one pole of a single Grove's cell (the other pole being to earth) was sufficient to produce coalescence of the drops. *Proc. Royal Society*, Feb. 27, 1879.

660. Waterspouts.—Waterspouts, being often accompanied by strong manifestations of electricity, have been ascribed by Peltier

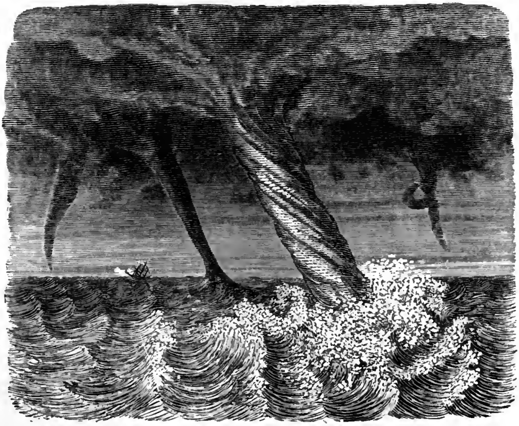


Fig. 414.—Waterspouts.

and others to an electrical origin; but the account of them given in the subjoined note appears more probable.[1]

[1] "On account of the centrifugal force arising from the rapid gyrations near the centre of a tornado, it must frequently be nearly a vacuum. Hence when a tornado passes over a building, the external pressure, in a great measure, is suddenly removed, when the atmosphere within, not being able to escape at once, exerts a pressure upon the interior, of perhaps nearly fifteen pounds to the square inch, which causes the parts to be thrown in every direction to a great distance. For the same reason, also, the corks fly from empty bottles, and everything with air confined within explodes. When a tornado happens at sea, it generally produces a waterspout. This is generally first formed above, in the form of a cloud shaped like a funnel or inverted cone. As there is less resistance to the motions in the upper strata than near the earth's surface, the rapid gyratory motion commences there first. . . . This draws down the strata of cold air above, which, coming in contact with the warm and moist atmosphere ascending in the middle of the tornado, condenses the vapour and forms the funnel-shaped cloud. As the gyratory motion becomes more violent, it gradually overcomes the resistances nearer the surface of the sea, and the vertex of the funnel-shaped cloud gradually descends lower, and the imperfect vacuum of the centre of the tornado reaches the sea, up which the water has a tendency to ascend to a certain height, and thence the rapidly ascending spiral motion of the atmosphere carries the spray upward, until it joins the cloud above, when the waterspout is complete. The upper part of a waterspout is frequently formed in tornadoes on land. When tornadoes happen on sandy plains, instead of waterspouts they produce the moving pillars of sand which are often seen on sandy deserts."—W. Ferrel, in *Mathematical Monthly*.

MAGNETISM.

CHAPTER LI.

GENERAL STATEMENT OF FACTS AND LAWS.

661. Magnets, Natural and Artificial.—Natural magnets, or *lodestones*, are exceedingly rare, although a closely allied ore of iron, capable of being strongly acted on by magnetic forces, and hence called *magnetic iron-ore,* is found in large quantity in Sweden and elsewhere. Artificial magnets are usually pieces of steel, which have been permanently endowed with magnetism by methods which we shall hereafter describe. Magnets are chiefly characterized by the property of attracting iron, and by the tendency to assume a particular orientation when freely suspended.

662. Force Greatest at the Ends.—The property of attracting iron is very unequally manifested at different points of the surface of a magnet. If, for example, an ordinary bar-magnet be plunged in iron-filings, these cling in large quantity to the terminal portions, and leave the middle bare, as in the lower diagram of Fig. 415. If the magnet is very thick in proportion to its length, we may have filings adhering to all parts of it, but the quantity diminishes rapidly towards the middle. The name *poles* is used, in a somewhat loose sense, to denote the two terminal portions of a magnet, or to denote two points, not very accurately defined, situated in these portions. The middle portion, to which the filings refuse to adhere, is called *neutral.*

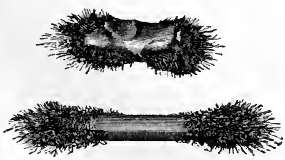


Fig. 415.—Magnets dipped in Filings.

663. Lines Formed by Filings.—If a sheet of card is laid horizontally upon a magnet, and wrought-iron filings are sifted over it, these will, with the assistance of a few taps given to the card, arrange

themselves in a system of curved lines, as shown in Fig. 416. These lines give very important indications both of the direction and intensity of the force produced by the magnet at different points of the

Fig. 416.—Magnetic Curves.

space around it.[1] They cluster very closely about the two poles p p, and thus indicate the places where the force is most intense.

664. Curve of Intensities.—Some idea may be obtained of the relative intensities of magnetic force at different points in the length of a magnet, by measuring the weights of iron which can be supported at them. Much better determinations can be obtained either by the use of the torsion-balance, or by counting the number of vibrations made by a small magnetized needle when suspended opposite different parts of the bar, the bar being in a vertical position, and the vibrations of the needle being horizontal. The intensity of the force is nearly as the square of the number of vibrations; on the same principle that the force of gravity at different places is proportional to the square of the number of vibrations of a pendulum (§ 120). Both these methods of determination were employed by Coulomb, who was the first to make magnetism an accurate science; and the results which he obtained are represented by the curve of intensities A M B (Fig. 417). M is the middle of the bar, O one end of it, and the ordinates

[1] The lines formed by the filings may be called the lines of *effective force for particles only free to move in the plane of the card.* The lines of total force cut the card at various angles, and are at some places perpendicular to it, as shown by the filings standing on end. For the definition of lines of magnetic force, see § 672.

of the curve (that is, the distances of its points from the line O X) represent the intensities of force at the different points in its length. The curve was constructed from observations of the force at several points in the length; but in dealing with the observation made opposite the very end, the force actually observed was multiplied by 2. Perfect symmetry was found between the intensities over the two halves of the length. In the figure we have inverted the curve for one-half, in order to indicate an opposition of properties, which we shall shortly have to describe. The curves of intensities for two magnets of different sizes but of the same form are usually similar.

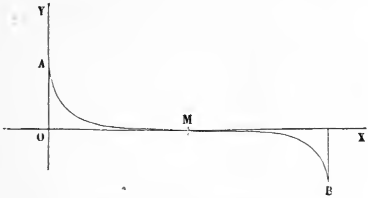


Fig. 417.—Curve of Intensities.

665. Magnetic Needle.—Any magnet freely suspended near its centre is usually called a *magnetic needle*, or more properly a *magnetized needle*. One of its most usual forms is that of a very elongated rhombus of thin steel, having, very near its centre, a concavity or *cup* by means of which it can be balanced on a point. When it is thus balanced horizontally, it does not, like a piece of ordinary matter, remain in equilibrium in all azimuths,[1] but assumes one particular direction, to which it always comes back after displacement. In this position of stable equilibrium, one of its ends points to magnetic north, and the other to magnetic south, which differ in general by several degrees from geographical (or true) north and south. This is the principle on which compasses are constructed.

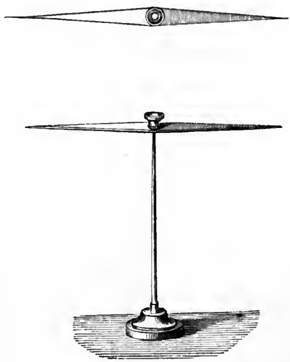


Fig. 418.—Magnetized Needle.

[1] All lines in the same vertical plane are said to have the same *azimuth*. Azimuthal angles are angles between vertical planes, or between horizontal lines. The azimuth of a line when stated numerically, is the angle which the vertical plane containing it makes with a vertical plane of reference, and this latter is usually the plane of the meridian. Some

666. Declination.—The difference between magnetic and true north, or the angle between the magnetic meridian and the geographical meridian, is called *magnetic declination.*[1] It is very different at different places, and at a given place undergoes a gradual change from year to year, besides smaller changes, backwards and forwards, which are continually taking place. At Greenwich, at the present time, its value is about 19° W., that is, magnetic north is west of true north by this amount.

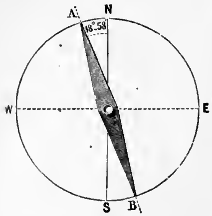


Fig. 419.—Declination.

667. Inclination or Dip.—If, before magnetizing a needle, we mount it on an axis passing through its centre of gravity, and support the ends of the axis, as in Fig. 420, by a thread without torsion, the needle will remain in equilibrium in any position in which it may be placed. If it be then magnetized, it will no longer be indifferent, but will place itself in a particular vertical plane called the magnetic meridian, and will take a particular direction in this plane. This direction is not horizontal, but inclined, generally at a considerable angle, to the horizon; and this angle is called *dip* or *inclination.* Its value at Greenwich is about $67\frac{1}{2}$°, the end which points to the north pointing at the same time downwards. In the northern hemisphere generally, it is the north end of the needle which dips, and in the southern hemisphere it is the end which points south.

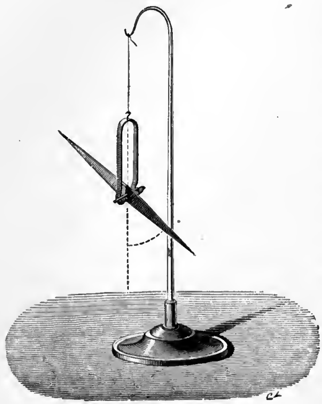


Fig. 420.—Dip.

readers may be glad to be reminded that by the plane of the *meridian* is meant a vertical plane passing through the place of observation, and through or parallel to the earth's axis. A horizontal line in this plane is a meridian line. The *magnetic meridian* is the vertical plane in which a magnetized needle, when freely suspended, tends to place itself.

[1] The nautical name for magnetic declination is *variation;* but it is most inconvenient and confusing to denote the element itself by the same name as the variations of the element.

It follows that, if a magnetized needle is to be balanced in a horizontal position, the point or axis of support must not be in the same vertical with the centre of gravity, but must be between the centre of gravity and the end which tends to dip. Needles thus balanced, as in the ordinary mariner's compass, are called *declination needles.*

668. Mutual Action of Poles.—On presenting one end of a magnet to one end of a needle thus balanced, we obtain either repulsion or attraction, according as the pole which is presented is similar or dissimilar to that to which it is presented. *Poles of contrary name attract each other; poles of the same name repel each other.*

This property furnishes the means of distinguishing a body which is merely magnetic (that is, capable of temporary magnetization) from a permanent magnet. The former, a piece of soft iron for example, is always attracted by either pole of a magnet; while a body which has received permanent magnetization has, in ordinary cases, two poles, of which one is attracted where the other is repelled. Magnetic attractions and repulsions are exerted without modification through any body which may be interposed, provided it be not magnetic.

669. Names of Poles.—The phenomena of declination and inclination above described, evidently require us to regard the earth, in a broad sense, as a magnet, having one pole in the northern and the other in the southern hemisphere. Now since poles which attract one another are dissimilar, it follows that the magnetic pole of the earth which is situated in the northern hemisphere is *dissimilar* to that end of a magnetized needle which points to the north. Hence great confusion of nomenclature has arisen, the usage of some of the best writers being opposite to that which generally prevails. We shall call that end or pole of a needle which seeks the north, the *north-seeking* end or pole, and the other the *south-seeking* end or pole. Sir Wm. Thomson calls the north-seeking pole the *south* pole, and the other the *north* pole, because the former is similar to the south, and the latter to the north pole of the earth. In like manner most French writers call the north-seeking pole of a needle the *austral,* and the other the *boreal* pole. Popular usage in this country calls the north-seeking end the *north,* and the other the *south* pole, a nomenclature which introduces great confusion whenever we have to reason respecting the earth regarded as a magnet. Faraday, to avoid the ambiguity which has attached itself to the names north and south pole, calls the north-seeking end the *marked,* and the other

the *unmarked* pole. Airy, for a similar reason, employs, in his recent *Treatise on Magnetism,* the distinctive names *red* and *blue* to denote respectively the north-seeking and south-seeking ends, these names, as well as those employed by Faraday, being purely conventional, and founded on the custom of marking the north-seeking end of a magnet with a transverse notch or a spot of red paint. Maxwell and Jenkin, in a report to the British Association,[1] call the south-seeking pole of a needle *positive,* and the north-seeking pole *negative.*

670. Magnetic Induction.—When a piece of iron is in contact with

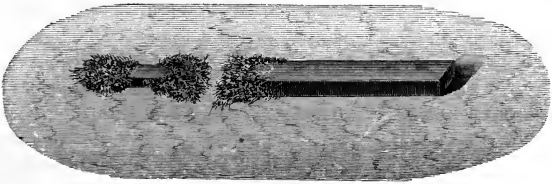


Fig. 421.—Induced Magnetism.

a magnet, or even when a magnet is simply brought near it, it becomes itself, for the time, a magnet, with two poles and a neutral portion between them. If we scatter filings over the iron, they will adhere to its ends, as shown in Fig. 421. If we take away the influencing magnet, the filings will fall off, and the iron will retain either no traces at all or only very faint ones of its magnetization. If we apply similar treatment to a piece of steel, we obtain a result similar in some respects, but with very important differences in degree. The steel, while under the influence of the magnet, exhibits much weaker effects than the iron; it is much more difficult to magnetize than iron, and does not admit of being so powerfully magnetized; but, on the other hand, it retains its magnetization after the influencing magnet has been withdrawn. This property of retaining magnetism when once imparted has been (somewhat awkwardly) named *coercive force.* Steel, especially when very hard, possesses great coercive force; iron, especially when very pure and soft, scarcely any.

In magnetization by influence, which is also called *magnetic induction,* it will be found, on examination, that the pole which is next the inducing pole is of contrary name to it; and it is on account of the mutual attraction of dissimilar poles that the iron is attracted

[1] *Report of Electrical Standards Committee,* Appendix C. 1863.

by the magnet. The iron can, in its turn, support a second piece of iron; this again can support a third, and so on through many steps. A magnetic chain can thus be formed, each of the component pieces having two poles. An action of this kind takes place in the clusters of filings which attach themselves to one end of a magnetized bar, these clusters being composed of numerous chains of filings.

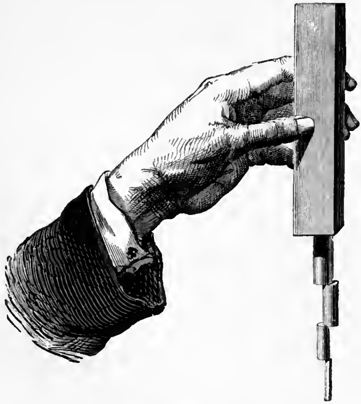


Fig. 422.—Magnetic Chain.

In comparing the phenomena of magnetic induction with those of electrical induction, we find both points of resemblance and points of difference. In the case of electricity, if the influencing and influenced body are allowed to come in contact, the former loses some of its own charge to the latter. In the case of magnetism there is no such loss, a magnet after touching soft iron is found to be as strongly magnetized as it was before.

671. Effect of Rupture on a Magnet.—If a magnet is broken into any number of pieces, every piece will be a complete magnet with

Fig. 423.—Broken Magnet.

poles of its own. In the case of an ordinary bar-magnet or needle, the similar poles of the pieces will all be turned the same way, as in Fig. 423, which represents a magnet A B broken into four pieces. The ends a, a, a, a are of one name, and the ends b, b, b, b of the opposite name.

672. Imaginary Magnetic Fluids: Magnetic Potential.—All mutual forces between magnets can be reduced to attractions and repulsions between different portions of two imaginary fluids,[1] one of which

[1] Poisson, following Coulomb, spoke of *two magnetic fluids*, and laid down a theory of

may be called *positive* and the other *negative.* Neither fluid can exist apart from the other; every magnet possesses equal quantities of both; quantity being measured by force of attraction or repulsion at given distance, just as in the case of electricity, like portions repelling, and unlike portions attracting each other inversely as the square of the distance. Equal quantities of the two fluids, when co-existing at the same place, produce no resultant effect, and may be regarded as destroying each other.

With reference to these imaginary fluids, *magnetic potential* can be defined in the same way as electrical potential (§§ 601, 602, 611), and magnetic *lines of force* possess the same properties as electrical lines of force (§§ 603, 604, 607, 608). The direction of magnetic force at a point can either be defined as the direction in which a pole of a magnet would be urged if brought to the point, or as the direction in which a small magnetized needle, if brought to the point and balanced at its centre of gravity, would place its line of poles; and lines of magnetic force are lines to which this direction is everywhere tangential. It is important to remark that a linear piece of soft iron, though it sets its length along a line of force, does not travel along a line of force, but deviates towards the concave side. This is easily shown by tapping the card represented in Fig. 416. It will be found that filings placed on the line *m m* move along that line, and therefore at right angles to the lines of force.

The force which is specified by magnetic "lines of force" is the force which *one pole* of a permanent magnet would experience; and it is the same in intensity, but opposite in direction, for dissimilar poles. The two poles of a small magnet (temporary or permanent) in the position of stable equilibrium as regards rotation, are pulled in nearly opposite directions; and the force which tends to produce movement of translation is the resultant of these two nearly opposite pulls. The direction of this resultant for a small sphere is the direction in which the intensity of the field increases most rapidly.

673. Specification of Magnetization.—A piece of steel is said to be *uniformly magnetized*, if equal and similar portions, cut in parallel directions from all parts of it, are precisely alike in their magnetic properties.

their action. Sir W. Thomson, avoiding the hypothetical parts of Poisson's theory, speaks of *imaginary magnetic matter* of two dissimilar kinds. We have retained the more familiar name *fluid*, simply because it is more convenient to speak of *two fluids* than of *two kinds of matter*. It is to be noted that we cannot speak of two *magnetisms*, the name magnetism having been already appropriated in a different sense.

If a piece of magnetized steel be suspended at its centre of gravity, so as to be free to turn all ways about it, the effect of the earth's magnetism upon it consists in a tendency for a particular line through this centre of gravity to take a determinate direction, which is the direction of terrestrial magnetic force. When the line is placed in any other position, the couple tending to bring it back is proportional to the sine of the angle between the two positions, and is the same for all directions of deviation. The line which possesses this property is the *magnetic axis* of the body, and the name is sometimes given to all lines parallel to it. If the piece of steel be uniformly magnetized, this axis is the direction of magnetization; or the *direction of magnetization is the common direction of all those lines which tend to place themselves along lines of force* in a field[1] where the lines of force are parallel.

674. Ideal Simple Magnet: Thin Bar, uniformly and longitudinally Magnetized.—The mutual actions of magnets admit of very accurate expression when the magnets are very thin in comparison with their length, uniform in section, and uniformly magnetized in the direction of their length. Such bars, which may be called *simple magnets*, behave as if their forces resided solely in their ends, which may therefore in the strictest sense be called their poles. The two poles of any one such bar are equal in strength; that is to say, one of them attracts a pole of another simple magnet with the same force with which the other repels it at the same distance. In the language of the two-fluid theory, the two fluids destroy one another except at the two ends, and the quantities which reside at the ends are equal but of opposite sign. The same number which denotes the quantity of fluid at either pole, denotes the *strength of the pole*, or, as it is often called, the *strength of the magnet*. Its definition is best expressed by saying that the force between a pole of one simple magnet and a pole of another, is the product of their strengths divided by the square of the distance between them.[2]

[1] A *field of force* is any region of space traversed by lines of force; or, in other words, any region pervaded by force of attraction or repulsion. A *magnetic field* is any region pervaded by magnetic force. All space in the neighbourhood of the earth is a magnetic field, and within moderate distances the lines of force in it may be regarded as parallel, unless artificial magnets or pieces of iron are present to produce disturbance.

[2] We here, and throughout the remainder of this chapter, ignore the existence of induction, which, however, is not altogether absent even in the hardest steel. The effect of induction is always to favour attraction. The attractions will therefore be somewhat stronger, and the repulsions somewhat weaker, than our theory supposes.

The force which a pole of a simple magnet experiences in a magnetic field, is the *product of the strength of the pole and the intensity of the field.* This rule applies to the force which a pole experiences from the earth's magnetism, the intensity of the field being in this case the intensity of terrestrial magnetic force; and, from the uniformity of the field, the forces on the two poles are in this case equal, constituting a couple, whose arm is the line joining the poles multiplied by the sine of the angle which this line makes with the lines of force.

The product of the line joining the two poles by the strength of either pole is called the *moment of the magnet,* and it is evident, from what has just been said, that the continued product of *the moment of the magnet, the intensity of terrestrial magnetic force, and the sine of the angle between the length of the magnet and the lines of force,* is equal to the moment of the couple which the earth's magnetism exerts upon the magnet.

675. Compound Magnet of Uniform Magnetization.—Any magnet which is not a simple magnet in the sense defined in § 674 may be called a *compound magnet.* It is convenient to define the moment of a compound magnet by the condition stated in the concluding words of that section, so that the moments of different magnets, whether simple or compound, may be compared by comparing the couples exerted on them by terrestrial magnetism when their axes are equally inclined to the lines of force.

If a number of simple magnets of equal strength be joined end to end, with their similar poles pointing the same way, there will be mutual destruction of the two imaginary fluids at every junction, and the system will constitute one simple magnet of the same strength as any one of its components; but its moment will evidently be the sum of their moments.

If any number of simple magnets be united, either end to end or side to side, provided only that they are parallel, and have their similar poles turned the same way, the resultant couple exerted upon the whole system by terrestrial magnetism will (§ 27) be the sum of the separate couples exerted on each simple magnet, and the moment of the system will be the sum of the moments of its parts. But any piece of uniformly magnetized material may be regarded as being thus built up, and hence, if different portions be cut from the same uniformly magnetized mass, their moments will be simply proportional to their volumes. The quotient of moment by volume, for any uniformly magnetized mass, is called *intensity of magnetization.*

676. Actual Magnets.—The definitions and laws of simple magnets are approximately applicable to actual magnets, when magnetized in the usual manner.

If an actual bar-magnet in the form of a rectangular parallelepiped were magnetized with perfect uniformity, and in the direction of its length, it might be regarded as made up of a number of simple magnets laid side by side, and its behaviour would be represented by supposing a complete absence of magnetic fluid from all parts of it except its *ends* (in the strict mathematical sense). One of these terminal faces would be covered with positive, and the other with negative fluid, and if the magnet were broken across at any part of its length, the quantities of positive and negative fluid on the broken ends would be the same as on the ends of the complete magnet. The observed fact that magnets behave as if the fluids were distributed through a portion of their substance in the neighbourhood of the ends, and not confined to the ends strictly so called, indicates a falling off in magnetization towards the extremities, and is approximately represented by conceiving of a number of short magnets laid end to end, and falling off in strength towards the two extremities of the series.[1]

The resultant force due to the imaginary magnetic fluids which are distributed through the terminal portions of an actual bar-magnet is, in the case of actions at a great distance, sensibly the same as if the two portions of fluid were collected at their respective centres of gravity. These two centres of gravity are the poles of the magnet for all actions between the magnet and other magnets at a great distance, and more especially between the magnet and the earth.

The moment of any magnet, however irregular in its magnetization, may be defined by reference to the expression given in § 674 for the couple exerted on the body by terrestrial magnetism. This couple is $M I \sin \alpha$, where I denotes the intensity of terrestrial magnetic force, α the inclination of the magnetic axis of the body to the lines of the earth's magnetic force, and M the *moment* which we are defining.

[1] Thus the last magnet at the positive end being weaker than its neighbour, its negative pole will be weaker than its neighbour's positive pole, so that there will be an excess of positive fluid at this junction. Similar reasoning applies to all the junctions near the ends. There will be an excess of positive fluid at all junctions near the positive end, and an excess of negative at all junctions near the negative end.

CHAPTER LII.

EXPERIMENTAL DETAILS.

677. The Earth's Force simply Directive.—The forces which produce the orientation of a magnet depend upon causes of which very little is known. They are evidently connected in some way with the earth, and are accordingly referred to TERRESTRIAL MAGNETISM. We have already stated (§ 673) that the combined effect of the forces exerted by terrestrial magnetism upon a magnetized needle is equivalent to a couple tending to turn the needle into a particular direction, and (§ 676) that in the case of needles magnetized in the ordinary way, there are two definite points or poles (near the two ends of the needle) which may be regarded as the points of application of the two equal forces which constitute the couple.

The fact that terrestrial magnetic force simply tends to turn the needle, and not to give it a movement of translation, in other words, that the resultant *force* (as distinguished from *couple*) is zero, is completely proved by the two following experiments:—

(1) If a bar of steel is weighed before and after magnetization, no change is found in its weight. This proves that the vertical component is zero.

(2) If a bar of steel, not magnetized, is suspended by a long and fine thread, the direction of the thread is of course vertical. If the bar is then magnetized, the direction of the thread still remains vertical. The most rigorous tests fail to show any change of its position. This proves that the horizontal component is zero, a conclusion which may be verified by floating a magnet on water by means of a cork. It will be found that there is no tendency to move across the water in any particular direction.

678. Horizontal, Vertical, and Total Intensities.—If S denote the strength of a magnet, and I the intensity of terrestrial magnetic force,

each pole of the magnet experiences a force SI, and if L denote the distance between the poles (often called the length of the magnet), the distance between the lines of action of these two parallel and opposite forces may have any value intermediate between L and zero, according to the position in which the needle is held. It will be zero when the line of poles is that of the dipping-needle; it will be L when the line of poles is perpendicular to the dipping-needle; and will be L sin α when the line of poles is inclined at any angle α to the dipping-needle.

The force SI upon either pole of the magnet acts in the direction of the dipping-needle; in other words, in the direction of the lines of force due to terrestrial magnetism. Let δ denote the dip, that is the inclination of the lines of force to the horizon, then the force SI can be resolved into SI cos δ horizontal, and SI sin δ vertical. Hence the horizontal and vertical intensities H and V are connected with the total intensity and dip I and δ by the two equations

$$H = I \cos \delta \quad , \quad V = I \sin \delta \qquad (1)$$

which are equivalent to the following two

$$\frac{V}{H} = \tan \delta \quad , \quad V^2 + H^2 = I^2. \qquad (2)$$

679. Torsion-balance.—Coulomb, in investigating the laws of the mutual action of magnets, employed a torsion-balance scarcely differing from that which he used in his electrical researches. The suspending thread carried, at its lower end, a stirrup on which a magnetized bar was laid horizontally. The torsion-head was so adjusted that one end of the magnet was opposite the zero of the divisions on the glass case when the supporting thread was without torsion. In order to effect this adjustment, the magnet was first suspended by a thread whose torsional power was inconsiderable, so that the magnet placed itself in the magnetic meridian. The case was then turned till its zero came to this position. The torsionless thread was then replaced by a fine metallic wire, and the magnet was replaced by a copper bar of the same weight. The head was then turned till this bar came into the magnetic meridian, and lastly the magnet was put in the place of the bar.

Fig. 424 shows the arrangement adopted for observing the repulsion or attraction between one pole of the suspended magnet and one pole of another magnet placed vertically. Before the insertion of the latter, the suspended magnet was acted on by no horizontal

forces except the horizontal component of terrestrial magnetism and the torsion of the wire. It was then found that the torsion requisite for keeping the magnet in any position was proportional to the sine of the displacement from the meridian.

This result is evidently in accordance with the principles stated

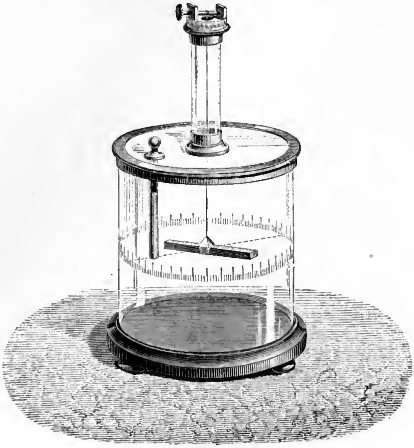


Fig. 424.—Torsion-balance.

above, for the two equal horizontal forces on the two poles being constant for all positions, the couple which they compose is proportional to the distance between their lines of action, and this distance is evidently L sin θ, L denoting the constant distance between the poles, and θ the deviation of the needle from the meridian.

680. Measurement of Declination.—Magnetic declination has been observed with several different forms of apparatus.

At sea, the most common method of determining it has consisted in observing the magnetic bearing of the rising or setting sun, and comparing this with its true bearing as calculated by a well-known astronomical method.

For more accurate determination on land, the declination compass or declination theodolite[1] (Fig. 425) has been frequently employed.

[1] A *theodolite* consists of a telescope mounted so as to have independent motions in

When the instrument is set, by the help of astronomical observations, so that the vertical plane in which the telescope L L′ (or more accurately its line of collimation) moves, coincides with the geographical meridian, the ends of the needle indicate the declination on the graduated circle over which they move. This circle in fact turns with the telescope, the line of 0° and 180° *n s* being always in the same vertical plane with the line of collimation of the telescope. The external divided circle PQ is used for setting the instrument in the meridian.

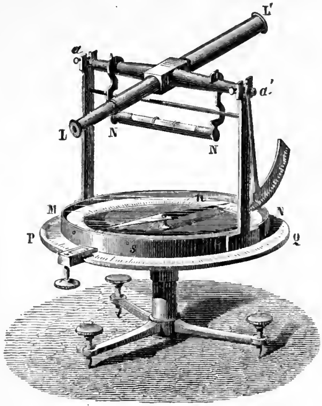


Fig. 425.—Declination Theodolite.

At fixed observatories more accurate methods of observation are employed. Fig. 426 shows the arrangement adopted at Greenwich. A bar-magnet B carries at one end a cross of fine threads C, and

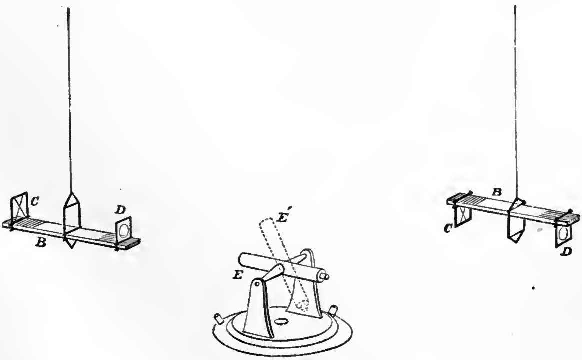


Fig. 426.—Declination Magnet.

azimuth and altitude, the amounts of these motions being indicated by divided circles or arcs of circles. It does not differ essentially from the larger instrument called the *altazimuth.*

at the other a lens D, the distance between them being equal to the focal length of the lens, thus forming a kind of inverted telescope, whose line of collimation is the line joining the cross to the optical centre of the lens. The bar is suspended by means of a stirrup from a torsionless thread, and sets its magnetic axis in the magnetic meridian. The telescope E, with theodolite mounting, is stationed opposite the end which carries the lens, and is so adjusted at each observation that its line of collimation is parallel to that of the inverted telescope carried by the magnet, an adjustment which is identified by seeing the cross C coincident with a similar cross fixed in the interior of the telescope E. When the observation has been made with the magnet in one position, it must be repeated with the magnet turned upside down as shown in the figure. Error of parallelism between the magnetic axis of the bar and the line of collimation of the inverted telescope which it carries, will affect these two observations to the same extent in opposite directions, and will therefore disappear from their mean. The readings are taken on a horizontal circle corresponding to the outer circle in Fig. 425, and astronomical observations must be made once for all to determine what reading corresponds to the geographical meridian.

Another very accurate method consists in rigidly attaching to the bar, instead of the lens and cross, a small vertical mirror. This can either be viewed through a telescope, so as to show the reflection of a horizontal scale of equal parts, which will appear to travel across the field of view of the telescope as the magnet turns, or it can be employed to throw the image of a spot of light either upon a screen viewed by the observer, or still better upon photographic paper drawn by clock-work, which leaves a permanent record of continuous changes. Both these methods of employing mirrors for the observation of small movements of rotation are now extensively employed in many applications. They appear to have been first introduced by Gauss, who employed them for the purpose which we are now considering.

681. Measurement of Dip.—The dip-circle or inclination compass is represented in Fig. 427. It consists essentially of a magnetized needle, very accurately and delicately mounted on a horizontal axis through its centre of gravity, in the centre of a vertical circle on which the positions of the two ends of the needle can be read off. This circle can be turned with the needle into any azimuth, the amount of rotation being indicated by a horizontal circle. It is obvious that, if the vertical circle is placed in the plane of the mag-

netic meridian, the needle, being free to move in this plane, will directly indicate the dip. On the other hand, if the vertical circle is placed in a plane perpendicular to the magnetic meridian, the horizontal component of terrestrial magnetism is prevented from moving the needle, which, accordingly, obeys the vertical component only, and takes a vertical position. In intermediate positions of the vertical circle, the needle will assume positions intermediate between the vertical and the true angle of dip. In fact, if θ be the angle which the plane of the vertical circle makes with the magnetic meridian, the component H $\sin\theta$ of terrestrial magnetism, being perpendicular to this plane, merely tends to produce pressure against the supports, and the horizontal component influencing the position of the needle is only H $\cos\theta$, which lies in the plane of the circle. As none of the vertical force is destroyed, the tangent of the apparent dip will be $\frac{V}{H\cos\theta}=\frac{\tan\delta}{\cos\theta}$. The most accurate method of setting the vertical circle in the magnetic meridian consists in first adjusting it so that the needle takes a vertical position, and then turning it through 90°.

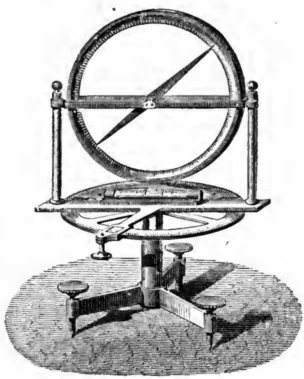


Fig. 427.—Dip-circle.

The instrument having thus been set, and a reading taken at each end of the needle, it should be turned in azimuth through 180°, and another pair of readings taken. By employing the mean of these two pairs of readings, several sources of error are eliminated, including non-coincidence of the axis of magnetization with the line joining the ends of the needle. One important source of error—deviation of the centre of gravity from the axis of suspension in a direction parallel to the length of the needle, is, however, not thus corrected. It can only be eliminated by remagnetizing the needle in the reverse direction so as to interchange its poles. The mean of the results obtained before and after the reversal of its magnetization will be the true dip.

A better form of instrument, known as the Kew dip-circle, is now

employed. Its essential parts are represented in Fig. 428. There is no metal near the needle, and the readings are taken on a circle round which two telescopes travel. In each observation the telescopes are directed to the two ends of the needle.

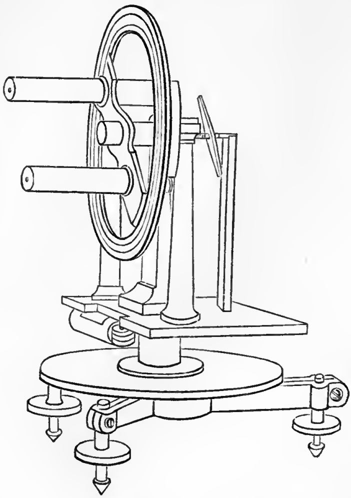


Fig. 428.—Kew Dip-circle.

682. Measurement of Intensity of Terrestrial Magnetic Force.—The complete specification of the earth's magnetic force at any place involves three independent elements. For example, if declination, dip, and horizontal force are determined by observation, vertical force and total force can be calculated by the formulæ of § 678.

Observations of magnetic force are made either by counting the number of vibrations executed in a given time, or by statical measurements. If a magnet executes small horizontal vibrations under the influence of the earth's magnetism, the square of the number of vibrations in a given time is proportional to $\frac{HM}{\mu}$, H denoting the horizontal intensity, M the moment of the magnet, and μ its moment of inertia about the centre of suspension. Hence it is easy to observe the *variations* of horizontal intensity which occur from time to time, if we can insure that our magnet itself shall undergo no change, or if we have the means of correcting for such changes as it undergoes. To obtain absolute determinations of horizontal intensity, the following method is employed.

First, observe the time of vibration of a freely-suspended horizontal magnet under the influence of the earth alone,—this will give the *product* of the earth's horizontal intensity and the moment of the magnet.

Secondly, employ this same magnet to act upon another also freely

suspended, and thus compare its influence with that of the earth,—this will give the ratio of the same two quantities whose product was found before. Hence the two quantities themselves can easily be computed.

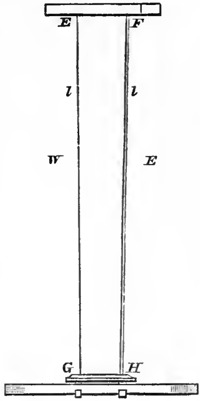


Fig. 429.—Bifilar Magnetometer.

683. Bifilar and Balance Magnetometers.—The changes of horizontal intensity are measured statically by means of the bifilar magnetometer. This consists of a bar-magnet (Fig. 429) suspended by two equal threads which would be in one vertical plane if the bar were unmagnetized; but matters are so arranged that, under the combined action of the pull of the threads, the weight of the bar, and the earth's magnetism, the bar is kept in a position nearly perpendicular to the magnetic meridian. The changes which occur in its position from time to time are due only to changes in the *intensity* of the earth's horizontal force; changes in the direction of this force, to the extent of a few minutes of angle, having no sensible effect, on account of the near approach to perpendicularity.

Let the distance E F of the upper points of attachment of the threads be $2a$ and the distance G H of the lower points $2b$, and let the angle between the directions of EF and GH be ϕ. Also let W be the weight of the magnet, l the length of each thread, T its tension, and θ its inclination to the vertical. In Fig. 430 E′, F′ are the projections of E, F upon the horizontal plane, which contains G, H; and the two lines GH, E′F′ bisect each other at O, so that we have $OE'=a$, $OG=b$, $E'OG=\phi$.

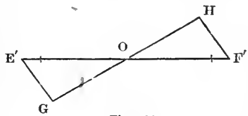


Fig. 430.

GE′ is the projection of one of the threads; we have therefore $GE'=l\sin\theta$, and the tension of this thread can be resolved into a vertical component $T\cos\theta$ and a horizontal component which acts along GE′, and is $T\sin\theta$ or $T\frac{GE'}{l}$. The moment of the latter round O is found by multiplying by the perpendicular dropped from O upon GE′. But GE′ multiplied by this perpendicular is double the

area of the triangle E′OG, or is $ab \sin \phi$, hence the moment in question is equal to $\frac{T}{l} ab \sin \phi$; and as this is due to one thread only, the couple due to the two threads is $\frac{2T}{l} ab \sin \phi$, which is practically equal to $\frac{W}{l} ab \sin \phi$, since θ is practically so small that $\cos \theta$ may be taken as unity.

If M be the magnetic moment of the magnet, and H the earth's horizontal intensity, MH will be the horizontal magnetic couple acting on the magnet, if the axis of the latter is perpendicular to the magnetic meridian. If the deviation from perpendicularity be β the couple will be MH $\cos \beta$, and β is practically so small that $\cos \beta$ may be taken as unity. Since in the position of equilibrium the two couples balance each other, we have the equation

$$W \frac{ab}{l} \sin \phi = MH,$$

which shows that H varies as $\sin \phi$.

The changes of vertical intensity are measured by the *balance-magnetometer*, which consists of a bar-magnet placed in the magnetic meridian, and suspended on knife-edges like the beam of an ordinary balance. Its deviations from horizontality are measures of the changes of vertical intensity.

Both these instruments have mirrors attached to the magnet, which produce a photographic record of the movements of the magnet, on principles above explained.

The moment of a magnet varies with temperature, being diminished by something like one ten-thousandth part of itself for each degree Fahr. of increase, and increasing again at the same rate when the temperature falls. Hence magnetic observatories must be kept at a nearly uniform temperature. They must also be completely free from iron. No iron nails are allowed to be used in their construction, copper being employed instead.

684. Results of Observation.—The annexed figures[1] contain an approximate representation of the magnetic meridians and lines of equal dip over both hemispheres of the earth. These two systems of lines combined, furnish a complete specification of the *direction* of magnetic force at all parts of the earth's surface; but they indicate nothing as to *intensity*. The curves of equal total intensity have a

[1] For Figs. 426, 428, 429, 431, 432 we are indebted to the publishers of Airy's *Treatise on Magnetism.*

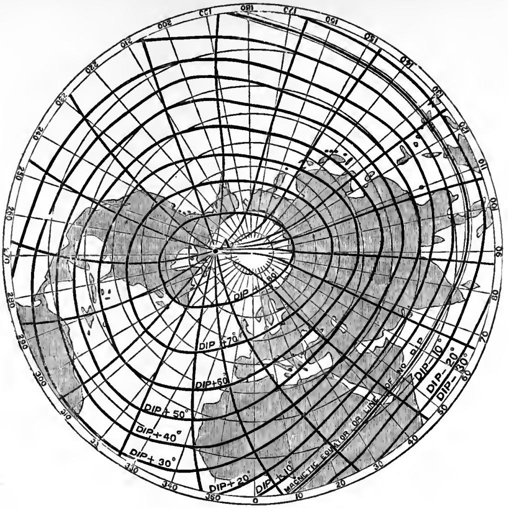


Fig 431.—Northern Hemisphere.

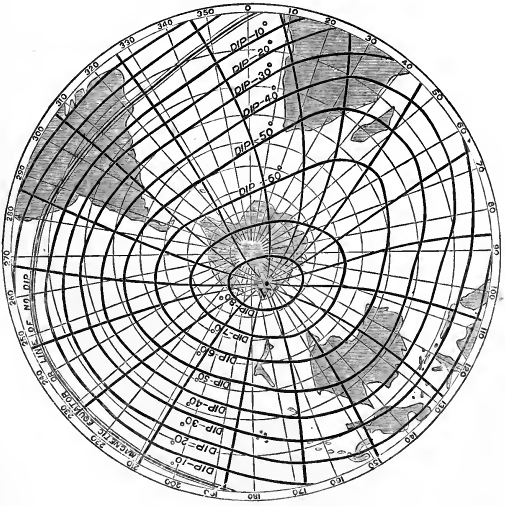


Fig. 432.—Southern Hemisphere.

MAGNETIC MERIDIANS AND LINES OF EQUAL DIP.

general resemblance to the lines of equal dip, the intensity being greatest near the poles, and least near the equator; but their arrangement is somewhat more complicated, there being two north poles of greatest intensity, one in Canada, and the other in the northern part of Siberia. Speaking roughly, the intensity near the poles is about double of the intensity near the equator. Curves of equal total intensity are often called *isodynamic* lines; curves of equal dip are often called *isoclinic* lines; curves of equal declination are often called *isogonic* lines; curves cutting the magnetic meridians at right angles are often called *magnetic parallels.* They are the lines which would be traced by continually travelling in the direction of magnetic east or west.

685. **The Earth as a Magnet.**—The intensity and direction of terrestrial magnetic force at different places may be *roughly* represented by supposing that there is a magnet $\pi\pi'$ (Fig. 433) at the earth's centre, having a length very small in comparison with the earth's radius, and making an angle of about 20° with the earth's axis of rotation. The points A and B obtained by producing this magnet longitudinally to meet the surface, would be the magnetic poles, and at any other place the magnetic meridian would be the vertical plane containing the magnetic axis A B. At places situated on the great circle whose plane contains both the axis of rotation and the magnetic axis, the magnetic meridian would coincide with the geographical meridian, and the declination would be zero. At any other place M, the two meridians would cut each other at an angle which would be the angle of declination. At all places on the great circle $\epsilon\epsilon'$ whose plane is perpendicular to the magnetic axis, a needle suspended at its centre of gravity would place itself parallel to this axis, and consequently the dip would be zero. This circle would be the magnetic equator.[1] It would cut

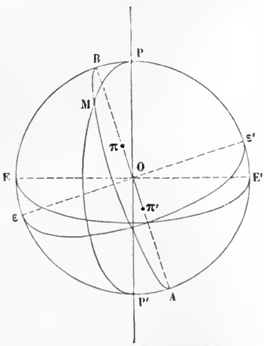


Fig. 433.—Biot's Hypothesis.

[1] If latitude reckoned from the magnetic equator be called magnetic latitude, and denoted by λ, it can be shown that we should have, on this theory,

$$\tan\delta = 2\tan\lambda;\ I = E\sqrt{\cos^2\lambda + 4\sin^2\lambda},$$

E denoting the intensity at the magnetic equator.

the geographical equator at an angle of 20°. Proceeding from the magnetic equator towards the north magnetic pole B, the needle would dip more and more, until at B it became vertical. A declination needle at B would remain indifferently in all positions. Similar phenomena would be observed at the other magnetic pole A. The end of the needle which would dip at B, and which at other parts of the earth would point to magnetic north, is that which is similar to the southern pole π' of the terrestrial magnet $\pi\pi'$, and the pole which is similar to π would dip at A.

The supposition of such a central magnet is known as *Biot's hypothesis*. It leads to the same results as the supposition that the earth is a uniformly magnetized sphere. For if we have a sphere built up of a number of equal and similar small magnets with their poles pointing the same way, we may suppose all the imaginary fluid at their northern ends to be collected at one central point, and all the imaginary fluid at their southern ends at another central point, the distance between these two points being equal to the common length of the small magnets. Hence the small central magnet will have the same moment as the uniformly magnetized earth.

The actual phenomena of terrestrial magnetism are much more irregular than the results to which this hypothesis leads. It would appear that the earth's magnetism is distributed in a manner not reducible to any simple expression.

686. Changes of Declination and Dip.—Declination and dip vary greatly not only from place to place, but also from time to time. Thus at the date of the earliest recorded observations at Paris, 1580, the declination was about 11° 30′ E. In 1663 the needle pointed due north and south, so that Paris was on the line of no declination. Since that time the declination has been west, increasing to a maximum of 22° 34′, which it attained in 1814. Since then it has gone on diminishing to the present time, its present value being about 19° W.

As to dip, its amount at Paris has continued to diminish ever since it was first observed in 1671. From 75° it has fallen to 66°, its present value. As its variations since 1863 have been scarcely sensible, it would seem to have now attained a minimum, to be followed by a gradual increase.

687. Magnetic Storms.—Besides the gradual changes which occur in terrestrial magnetism, both as regards direction and intensity of force, in the course of long periods of time, there are minute fluctua-

tions continually traceable. To a certain extent these are dependent on the varying position of the sun, and, to a much smaller extent, of the moon, with respect to the place of observation; but over and above all regular and periodic changes, there is a large amount of irregular fluctuation, which occasionally becomes so great as to constitute what is called a *magnetic storm*. Magnetic storms "are not connected with thunder-storms, or any other known disturbance of the atmosphere; but they are invariably connected with exhibitions of aurora borealis, and with spontaneous galvanic currents in the ordinary telegraph wires; and this connection is found to be so certain, that, upon remarking the display of one of the three classes of phenomena, we can at once assert that the other two are observable (the aurora borealis sometimes not visible here, but certainly visible in a more northern latitude)."[1] They are sensibly the same at stations many miles apart, for example at Greenwich and Kew, and they affect the direction and amount of horizontal much more than of vertical force.

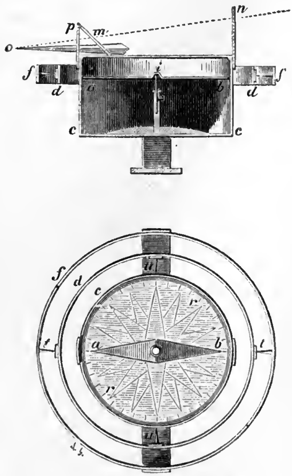


Fig. 434.—Ship's Compass.

688. Ship's Compass.—In a ship's compass, the box $c\,c$ (Fig. 434) which contains the needle is weighted below, and hung on gimbals, which consist of two rings so arranged as to admit of motion about two independent horizontal axes $t\,t$, $u\,u$ at right angles to each other. This arrangement prevents it from being tilted by the pitching and rolling of the ship. The needle $a\,b$ is firmly attached to the compass card, which is a circular card marked with the 32 points of the compass, as in Fig. 435, and also usually divided at its circumference into 360 degrees. The card with its attached needle is accurately balanced on a point at its centre. The needle, which, in actual use, is concealed from view, lies along the line N S. The box contains a vertical mark in its interior on the side next the ship's bow; and

[1] Airy on *Magnetism*, p. 204.

this mark serves as an index for reading off on the card the direction to which the ship's head is turned. Sometimes a reflector is employed, as m in the first part of Fig. 434, in such a position that an observer looking in from behind can read off the indicated direction by reflection, and can at the same time sight a distant object whose magnetic bearing is required. The origin of the compass is very obscure. The ancients were aware that the loadstone attracted iron, but were ignorant of its directive property. The instrument came into use in Europe some time in the course of the thirteenth century.

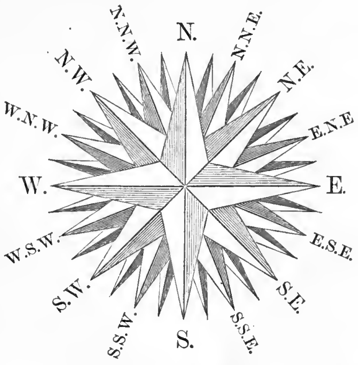
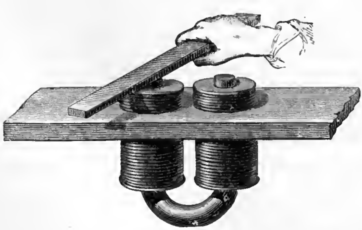


Fig. 435 —Compass Card.

689. Methods of Magnetization.—The usual process of magnetizing a bar consists in rubbing it with or against a bar already magnetized. Different methods of doing this, called single touch, double touch, &c., have been devised, in which magnetized bars of steel were the magnetizing agents. Much greater power can, however, be obtained by means of electro-magnetism; and the two following methods are now almost exclusively employed by the makers of magnets.

1. A fixed electro-magnet (Fig. 436) is employed, and the bar to



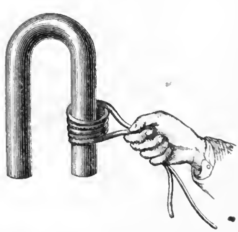


Fig. 436. Methods of Magnetization. Fig. 437.

be magnetized is drawn in opposite directions over its two poles. Each stroke tends to develop at the end of the bar at which the

motion ceases, the opposite magnetism to that of the pole which is in contact with it. Hence strokes in opposite directions over the two contrary poles tend to magnetize the bar the same way.

2. When very intense magnetization is to be produced, the electro-magnet must be very powerful, and the bar then adheres to it so strongly that the operation above described becomes difficult of execution, besides scratching the bar. Hence it is more convenient to move along the bar, as in Fig. 437, a coil of wire through which a current is passing. This was the method employed by Arago and Ampère.

A bar of steel is said to be magnetized to *saturation,* when its magnetization is as intense as it is able to retain without sensible loss. It is possible, by means of a powerful magnet, to magnetize a bar considerably above saturation; but in this case it rapidly loses intensity.

Pieces of iron and steel frequently become magnetized temporarily or permanently by the influence of the earth's magnetism, and this action is the more powerful as the direction of their length more nearly coincides with that of the dipping-needle. If fire-irons which have usually stood in a nearly vertical position be examined by their influence on a needle, they will generally be found to have acquired some permanent magnetism, the lower end being that which seeks the north.

It sometimes happens that, either from some peculiarity in the structure of a bar, or from some irregularity in the magnetizing pro-

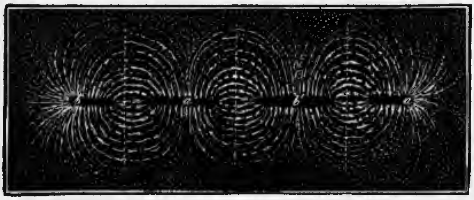


Fig. 438.—Conseqnent Points.

cess, a reversal of the direction of magnetization occurs in some part or parts of the length as compared with the rest. In this case the magnet will have not only a pole at each end, but also a pole at each point where the reversal occurs. These intermediate poles are called *consequent points.* Fig. 438 represents the arrangement of iron-

filings about a bar-magnet which has two consequent points a', b'. The whole bar may be regarded as consisting of three magnets laid end to end, the ends which are in contact being similar poles. Thus the two poles at a' and the one pole at a are of one kind, while the two poles at b' and the one pole at b are of the opposite kind.

The lifting power (or *portative* force) of a magnet generally increases with its size, but not in simple proportion, small magnets being usually able to sustain a greater multiple of their own weight than large ones. Hence it has been found advantageous to construct compound magnets, consisting of a number of thin bars laid side by side, with their similar poles all pointing the same way. Fig. 439 represents such a compound magnet composed of twelve elementary bars, arranged 4×3. Their ends are inserted in masses of soft iron, the extremities of which constitute the poles of the system.

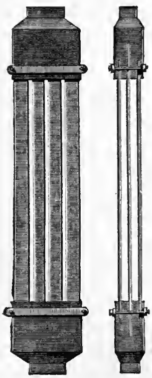


Fig. 439.—Compound Magnet.

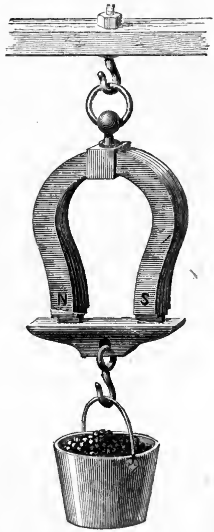


Fig. 440.—Compound Horse-shoe Magnet.

Fig. 440 represents a compound horse-shoe magnet, whose poles N and S support a keeper of soft iron, from which is hung a bucket for holding weights. By continually adding fresh weights day after day, the magnet may be made to carry a much greater load than it could have supported originally; but if the keeper is torn away from the magnet, the additional power is instantly lost, and the magnet is only able to sustain its original load.

Much attention was at one time given to methods of obtaining steel magnets of great power. These researches have now been superseded by electro-magnetism, which affords the means of obtaining temporary magnets of almost any power we please.

690. Molecular Changes accompanying Magnetization.—Joule has

shown that, when a bar of iron is magnetized longitudinally, it acquires a slight increase of length, compensated, however, by transverse contraction, so that its volume undergoes no change.

If the magnetization is effected suddenly, by completing an electric circuit, an ear close to the bar hears a clink, and another clink is heard when the current is stopped.

These phenomena have been accounted for by the hypothesis that, when iron is magnetized, its molecules place their longest dimensions in the direction of magnetization.

The effect of heat in diminishing the strength of a magnet is another instance of the connection between magnetism and other molecular conditions. In ordinary cases, this diminution is merely transient; but if a steel magnet is raised to a white-heat, it is permanently demagnetized.

691. Action of Magnetism on all Bodies.—It has long been known that iron and steel are not the only substances which can be acted on by magnetism. Nickel and cobalt especially were known to be attracted by a magnet, though very much more feebly than iron, while bismuth and antimony were repelled. Faraday, by means of a powerful electro-magnet, showed that all or nearly all substances in nature, whether solid, liquid, or gaseous, were susceptible of magnetic influence, and that they could all be arranged in one or the other of two classes, characterized by opposite qualities. This opposition of quality is manifested in two ways.

1. As regards attraction and repulsion, iron and other *paramagnetic* bodies are attracted by either pole of a magnet, or more generally, they tend to move from places of weaker to places of stronger force. On the other hand, bismuth and other *diamagnetic* bodies are repelled by either pole of a magnet, and in general tend to move from places of stronger to places of weaker force.

2. As regards orientation, a paramagnetic[1] body, when suspended between the poles of a magnet, tends to set *axially;* that is to say, tends to place its length along the line joining the poles; whereas a diamagnetic body tends to set *equatorially*, that is, to place its length at right angles to the line joining the poles.

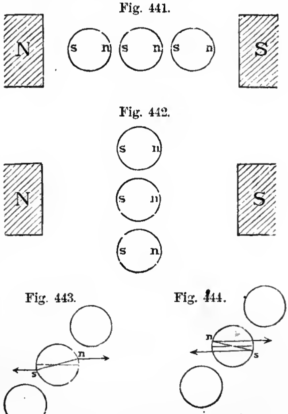
[1] The nomenclature here adopted was proposed by Faraday in 1850 (*Researches*, § 2790), and is eminently worthy of acceptance. Many writers, however, continue to employ *magnetic* in the exclusive sense of *para*magnetic. To be consistent, they should call the other class *anti*magnetic, not *dia*magnetic. "The word *magnetic* ought to be general, and include *all* the phenomena and effects produced by the power."

The fundamental difference is, that a piece of bismuth (or other diamagnetic substance), when it becomes a temporary magnet from the inductive influence of the field in which it is placed, has its poles opposite, end for end, to those of a piece of iron (or other paramagnetic substance) similarly placed. From this reversal of the poles, it follows that the resultant force upon the bismuth is opposite in direction to the resultant force upon the iron; and as the iron is urged from places of weaker to places of stronger force, the bismuth is urged from stronger to weaker. This is the cause of the equatorial setting of a diamagnetic bar when suspended between the poles of a magnet. It is merely a result of the tendency of the particles to move outwards into the regions of weaker magnetic action. In a uniform field, with parallel lines of force, the equatorial setting would not occur.

The axial setting of an iron bar between the poles of a magnet is jointly due to two causes, one being the tendency of its particles to move to places of stronger force, while the other cause, which we will now proceed to explain, tends to produce axial setting even in a uniform field.

692. Reason of Setting in a Uniform Field.—Suppose a row of iron balls placed axially, as in Fig. 441, either between the poles of a magnet, or along a line of force in uniform field; the force of the field being such as to urge a north pole from left to right. Each ball will, by induction, become a magnet with its north pole to the right, and the force which each ball experiences from its neighbours will be in the same direction as the force of the field. The mutual action of the balls, therefore, increases the induction due to the field.

Fig. 441. Fig. 442. Fig. 443. Fig. 444.



Figs. 441–444.—Reason of Setting in Uniform Field.

Next, suppose a row of iron balls placed equatorially in the same field (Fig. 442). The north pole of each ball will be attracted to the left by the south poles of its neighbours, and the induction due to the field will therefore be diminished.

Thirdly, let a row of iron balls be placed in a line inclined to the lines of force (Fig. 443). The force of the field can be resolved into two components, one (which we shall call the longitudinal component) along the line of balls, and the other (which we shall call the transverse component) normal to the line of balls. Mutual induction will, as above shown, augment the longitudinal and diminish the transverse component. It will, therefore, alter the direction of the total induction, so as to make it more nearly longitudinal. The poles of any one of the balls will therefore have such positions as are shown at n and s in the figure, n being above and s below the horizontal line through the centre.

In estimating the forces which tend to turn the row of balls as a whole when they are rigidly connected together, we must remember that mutual actions between different parts of a rigid body do not tend to move the body as a whole. Such motion can only be produced by forces from without, that is, in the present case, by the original force of the field, which urges north poles from left to right, and south poles from right to left. The forces on each ball will constitute a couple as shown by the two arrows in the figure, and these couples tend to turn the body into the axial position.

If we apply similar reasoning to a row of balls of bismuth, we shall find that mutual induction diminishes the longitudinal component, increases the transverse component, and in the case of the oblique row, gives the poles of each ball positions such as are shown in Fig. 444. The couple due to the external forces of the field is represented by the two arrows in the figure, and tends (just as in the case of iron) to turn the body into the axial position. This directive action is, however, excessively feeble, the forces due to mutual induction in bismuth being insensible in comparison with the external forces of the field.

693. Experimental Arrangements. Faraday's Apparatus.—Fig. 445 represents the apparatus commonly employed for experiments on this subject. B, B are two large coils of stout copper wire, wound on massive hollow cylinders of soft iron. These latter form portions of the heavy frames F, F, which can be slid to or from each other, and fixed firmly at any distance by means of the screws E, E. The armatures P, which can be screwed on or off, have the form of rounded cones, and produce a great concentration of force at their extremities.

The action of magnetism upon a solid can be examined by suspending a small bar of it *a b*, by means of a special support RS, between the poles P. When a current is passed through the coils, the bar immediately exhibits a preference either for the axial or the equatorial position. Attraction and repulsion are most easily tested by

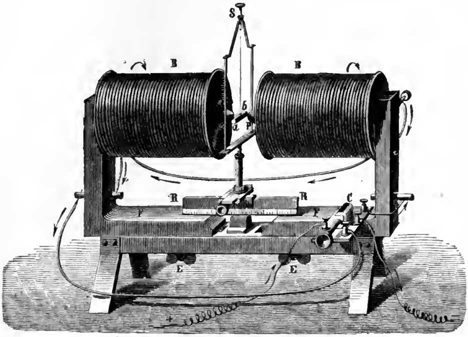


Fig. 445.—Apparatus for Diamagnetism.

suspending a small ball of the substance at the level of the central line of poles, but a little beside it, the poles having first been brought very near together. On passing the current through the coil, the ball will move inwards towards the line of poles if paramagnetic, and outwards if diamagnetic.

It is important, however, to remark, that experiments of this kind, unless performed *in vacuo*, are merely differential—they merely indicate that the suspended body is, in the one case, more paramagnetic or less diamagnetic; in the other case more diamagnetic or less paramagnetic, than the medium in which it moves, the comparison being made between equal volumes. Oxygen is paramagnetic, and nitrogen is nearly or quite indifferent. Air is accordingly paramagnetic, and a body suspended in air appears less paramagnetic or more diamagnetic than it really is. If more feebly paramagnetic than air, it will appear to be diamagnetic. Thus heated air, in consequence probably of its rarefaction, appears diamagnetic when surrounded by cold air, and the flame of a taper is repelled downwards and outwards from the axial line.

If, on the other hand, the body under examination is suspended

in water, it will appear more paramagnetic than it really is, by reason of the diamagnetism of water.

The following metals are paramagnetic: iron, nickel, cobalt, manganese, chromium, titanium, cerium, paladium, platinum, osmium.

The following are diamagnetic: bismuth, antimony, lead, tin, mercury, gold, silver, zinc, copper.

The following substances are also diamagnetic: water, alcohol, flint, glass, phosphorus, sulphur, resin, wax, sugar, starch, wood, ivory, beef (whether fresh or dried), blood (whether fresh or dried), leather, apple, bread.

694. Magneto-crystallic Action.—The orientation of crystals in a magnetic field presents some remarkable peculiarities, which were extremely perplexing to investigators until Tyndall and Knoblauch discovered the principle on which they depend. This principle is, that crystals are susceptible of magnetic induction to different degrees in different directions. Every crystal (except those belonging to the cubic system) has either one line or one plane along which induction takes place more powerfully than in any other direction; and it is this line or plane which tends to place itself axially or equatorially according as the crystal is paramagnetic or diamagnetic. The directions of most powerful and least powerful induction are found to be closely related to the optic axes of crystals, and also to their planes of cleavage. When a sphere cut from a crystal is brought near to one pole of a magnet, it is attracted or repelled (according as it is para- or dia-magnetic) with the greatest force when the direction of most powerful induction coincides with the direction of the force.

Directions of unequal induction can be produced artificially in non-crystalline substances by applying pressure. "Bismuth is a brittle metal, and can readily be reduced to a fine powder in a mortar. Let a tea-spoonful of the powdered metal be wetted with gum-water, kneaded into a paste, and made into a little roll, say an inch long and a quarter of an inch across. Hung between the excited poles, it will set itself like a little bar of bismuth—equatorial. Place the roll, protected by bits of pasteboard, within the jaws of a vice, squeeze it flat, and suspend the plate thus formed between the poles. On exciting the magnet, the plate will turn, with the energy of a magnetic substance, into the axial position, though its length may be ten times its breadth.

"Pound a piece of carbonate of iron into fine powder, and form it into a roll in the manner described. Hung between the excited

poles, it will stand as an ordinary [para]magnetic substance—axial. Squeeze it in the vice, and suspend it edgeways, its position will be immediately reversed. On the development of the magnetic force, the plate thus formed will recoil from the poles, *as if violently repelled,* and take up the equatorial position."[1]

In these experiments the direction of most powerful induction is a line transverse to the thickness, and this is also the direction in which pressure has been applied. Tyndall accordingly concludes that "if the arrangement of the component particles of any body be such as to present different degrees of proximity in different directions, then the line of closest proximity, other circumstances being equal, will be that chosen by the respective forces for the exhibition of their greatest energy. If the mass be [para]magnetic, this line will stand axial; if diamagnetic, equatorial."[2]

[1] Tyndall on *Diamagnetism.* p. 18.

[2] Ibid. p. 23.

CURRENT ELECTRICITY.

CHAPTER LIII.

GALVANIC BATTERY.

695. Voltaic Electricity.—Towards the close of last century, when the discovery of the various phenomena of frictional electricity had been followed by Coulomb's investigations, which first reduced them to an accurate theory, a new instrument was brought to light destined to effect a complete revolution in electrical science. In place of an element difficult to manage, capricious and uncertain in its behaviour, and constantly baffling investigation by the rapidity of its dissipation, the galvanic battery furnished a steady source of electricity, constantly available in all weathers, and requiring no special precautions to prevent its escape. Moreover, the electricity thus developed exhibited an entirely new set of phenomena, and opened up the way to such various and important applications, that frictional electricity at once fell into the second place, and the new agent became the main object of interest with all electrical investigators.

696. Galvanic Element.—If two plates, one of zinc and the other of copper (Fig. 446), are immersed in water acidulated by the addition of sulphuric acid, and are not allowed to touch each other within the acid, but are connected outside it, either by direct contact, or by a metallic wire M and binding screws, as in the figure, a continuous current of electricity flows round the circuit thus formed, the direction of the positive current being from copper to zinc in the portion external to the liquid, and from zinc to copper through the liquid. Chemical action at the same time takes place, the zinc being gradually dissolved by the acid, and hydrogen being given out at the copper plate.

If, instead of employing two metals and a liquid, we form a circuit with any number of metals alone, no current will be gena-

rated, provided that the whole circuit be kept at one temperature. If, however, some of the junctions be kept hot and others cold, a current will in general be produced.

The principles which underlie these phenomena appear to be as follows:—

(1). When two dissimilar substances touch each other, they have not exactly the same potential at the point of contact. For instance, when zinc is in contact with copper, it is at higher potential than the copper.

(2). The difference is in general greater for two metals than for a metal and a non-metal or two non-metals.

(3). The difference depends not only on the nature of the two substances, but also on their temperatures.

(4). The difference of potentials between two metals is the same when they are in direct contact as when they are connected by one or more intervening metals: all the metals being still supposed to be at the same temperature.

(5). When two metals are connected by a conducting liquid which is susceptible of decomposition, their difference of potential is much smaller than when they are in direct contact. Thus, if the connecting wire M (Fig. 446) be of copper, and we break its connection with the copper plate, the difference of potential between the two plates will be less than the difference between the zinc plate and the copper wire. The zinc plate is positive with respect to the copper wire; hence the copper plate is positive with respect to the copper wire. On completing the circuit, positive electricity accordingly flows from the copper plate into the copper wire. As the difference of potentials at the junction of the dissimilar metals is permanent, the current is permanently maintained. Chemical combination at the same time goes on; and the potential energy of chemical affinity which thus runs down, is the source of the energy of the current.

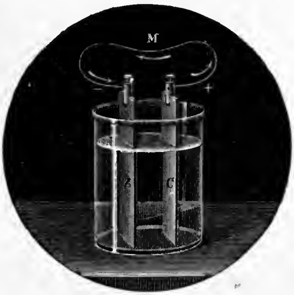


Fig. 446.—Voltaic Element.

Every electric current may be regarded as a flow of positive electricity in one direction, and of negative electricity in the opposite

direction. The direction in which the positive electricity flows is always spoken of as the *direction of the current.*

697. Galvanic Battery.—By connecting the plates of successive elements in the manner represented in Fig. 447, we obtain a battery. The copper of the first cell on the left hand is connected with the

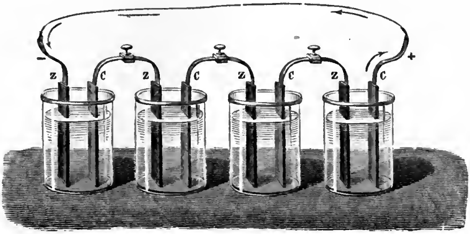


Fig. 447.—Battery of Four Elements.

zinc of the second; the copper of the second with the zinc of the third; and so on to the end of the series.

If two wires of the same metal be connected, one with the first zinc and the other with the last copper, the difference of potential between these wires is independent of the particular metal of which they are composed, and is called the *electro-motive force* of the battery. Its amount can be measured by means of Thomson's quadrant electrometer; and in applying this test, it is not necessary that the wires which connect the battery with the electrometer should be of the same metal; for, whatever metals these wires may be composed of, the quadrants of the electrometer will (by law (4) above) assume the same potentials as if in direct contact with the plates of the battery.

The zinc of the first and the copper of the last cell (or wires proceeding from them) are called the *electrodes* or *poles* of the battery, the zinc being the negative and the copper the positive electrode. The current flows through the connecting wire from the positive to the negative electrode, and is forced through the battery from the negative to the positive.

698. Galvani's Discoveries.—About the year 1780, Galvani, professor of anatomy at Bologna, had his attention called to the circumstance that some recently skinned frogs, lying on a table near an electrical machine, moved as if alive, on sparks being drawn from the machine.

Struck with the apparent connection thus manifested between electricity and vital action, he commenced a series of experiments on the effects of electricity upon the animal system. In the course of these experiments, it so happened that, on one occasion, several dead frogs were hung on an iron balcony by means of copper hooks which were in contact with the lumbar nerves, and the legs of some of them were observed to move convulsively. He succeeded in obtaining a repetition of these movements by placing one of the frogs on a plate of iron, and touching the lumbar nerves with one end of a copper wire, the other end of which was in contact with the iron plate. Another mode of obtaining the result is represented in Fig. 448, two wires of different metals being employed which touch each other at one end, while their other ends touch respectively the lumbar nerves and the crural muscles. Every time the contact is completed, the limb is convulsed.

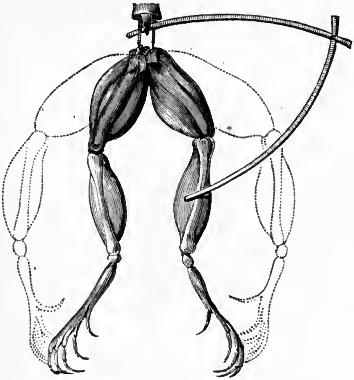


Fig. 448.—Experiment with Frog.

Galvani's explanation was, that at the junction of the nerves and muscles there is a separation of the two electricities, the nerve being positively, and the muscle negatively electrified, and that the convulsive movements are due to the establishment of communication between these two electricities by means of the connecting metals.

Volta, professor of physics at Pavia, disproved this explanation by showing that the movements could be produced by merely connecting two parts of a muscle by means of an arc of two metals; and he referred the source of electricity not to the junction of nerve and muscle, but to the junction of the two metals. Acting on this belief, he constructed in the year 1800 a voltaic pile.

699. Voltaic Pile.—This consisted of a series of discs of copper, zinc, and wet cloth, *c, z, d,* Fig. 449, arranged in uniform order, thus—copper, zinc, cloth, copper, zinc, cloth . . . the lowest plate of all being copper and the highest zinc. The wet cloth was intended

merely to serve as a conductor, and prevent contact between each zinc and the copper above it. All the contacts between zinc and copper were between a copper below and a zinc above, so that they all tended, according to Volta's theory, to produce a current of electricity in the

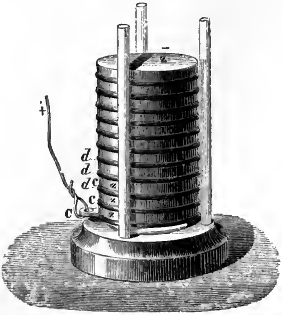


Fig. 449.—Structure of Pile.

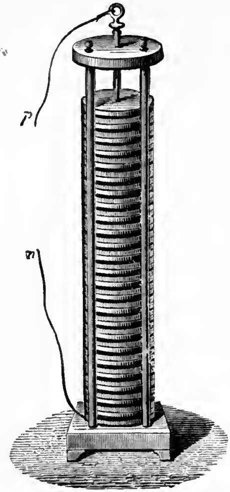


Fig. 450.—Complete Pile.

same direction. The effects obtained from the pile were so powerful as to excite extraordinary interest in the scientific world.

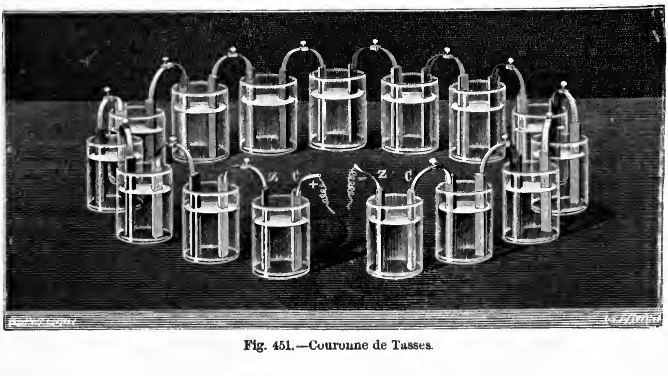


Fig. 451.—Couronne de Tasses.

700. Couronne de Tasses.—He shortly afterwards invented the

couronne de tasses (crown of cups), consisting of a series of cups arranged in a circle, each containing salt water with a plate of silver or copper and a plate of zinc immersed in it, the silver or copper of each cup being connected with the zinc of the next, with the exception of the extreme plates. The last plate in liquid at each end of the series was connected with a plate of the other metal in air. These two plates in air are now known to be useless, and are omitted in the figure.

701. Trough Battery.—More convenient arrangements, equivalent

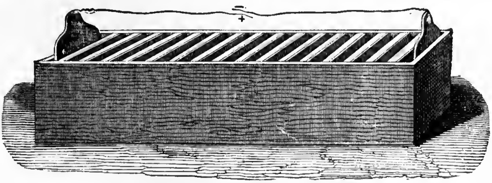


Fig. 452.—Cruickshank's Trough.

to the couronne de tasses, were soon introduced. One of these, devised by Cruickshank, is represented in Fig. 452, consisting of a rectangular box, called a trough, of baked wood, which is a non-conductor of electricity, divided into compartments by partitions each consisting of a plate of zinc and a plate of copper soldered together. Dilute acid is poured into these compartments.

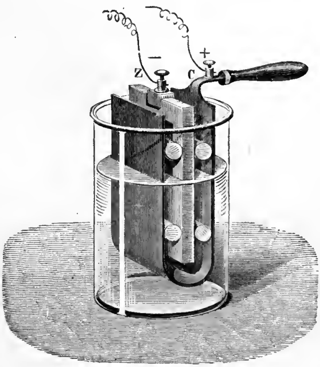


Fig. 453.—Wollaston's Cell.

702. Wollaston's Battery.—In Wollaston's battery, the plates were suspended from a single horizontal bar, by means of which they could all be let down into the acid, or lifted out of it together. The liquid was contained either in compartments of a trough of glazed earthenware, with partitions of the same material, or in separate vessels as shown in Fig. 454. The plates were double-coppered; that is to say,

they consisted of a zinc plate with a copper plate bent round it on

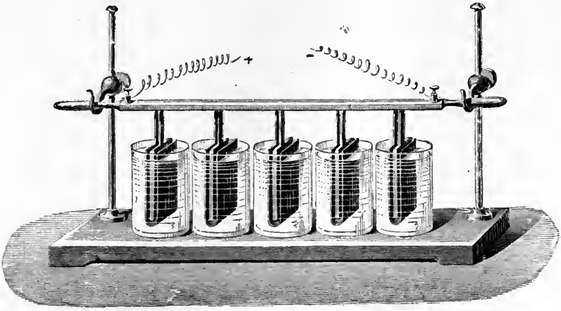


Fig. 454.—Wollaston's Battery.

both sides (Fig. 453), contact between them being prevented by pieces of wood or cork.

703. Hare's Deflagrator.—For some purposes it is more important to diminish the resistance of a cell, or, in other words, to facilitate the conduction of electricity between the zinc and the copper plate, than to increase the electro-motive force by multiplying cells. The helical arrangement devised by Hare of Philadelphia (Fig. 455) is specially adapted to such purposes. It consists of two very large plates of zinc and copper rolled upon a central cylinder of wood, and prevented from touching each other by pieces of cloth or twine inserted between them. It is plunged in a tub of acidulated water, as represented in the figure. From the remarkably powerful heating effects which can be obtained by the use of this cell, it is called Hare's *deflagrator*.

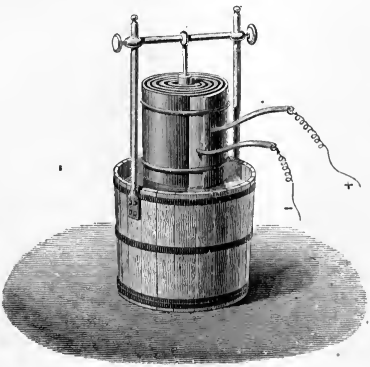


Fig. 455.—Hare's Deflagrator.

704. Polarization of Plates.—All the forms of battery which we have thus far described, are liable to a rapid decrease of power, owing to causes which are partly chemical and partly electrical.

The chemical action which takes place in each cell consists primarily in the formation of sulphate of zinc, at the expense of the zinc plate, the sulphuric acid, and the oxygen of the water with which the acid is diluted, the hydrogen of the water being thus liberated. As this action proceeds, the liquid becomes continually less capable of acting powerfully on the zinc. Again, a portion of the zinc which has been dissolved becomes deposited on the copper plate, thus tending to make the two plates alike, and so to destroy the current, which essentially depends on the difference between them.

But the most important cause of all is to be found in what is called the *polarization* of the copper plate; that is to say, in the deposition of a film of hydrogen on the surface of the plate. This film not only interposes resistance by its defect of conductivity, but also brings to bear an electro-motive force in the direction opposed to that of the current.

These obstacles to the maintenance of a constant current were first overcome by Daniell.

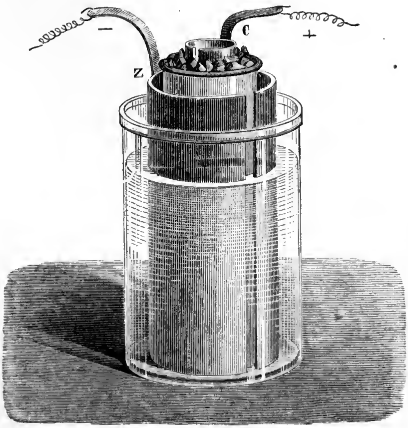


Fig. 456.—Daniell's Cell.

705. Daniell's Battery.—In the cell devised by Daniell, there is a porous partition of unglazed earthenware, separating the two liquids, which are in contact one with the zinc, and the other with the copper plate. These two liquids are not precisely alike, that which is in contact with the copper being not simply dilute sulphuric acid like the other, but containing also as much sulphate of copper as it will take up. For the purpose of keeping it saturated, crystals of sul-

phate of copper are suspended in it near its surface by means of a wire basket of copper. The effect of this arrangement is, that the hydrogen is intercepted before it can arrive at the copper plate, and the deposit which takes place on the copper plate is a deposit of copper, the hydrogen taking the place of this copper in the saturated solution.

The current given by a battery of these cells remains nearly constant for some hours.

In the figure, the copper plate C is represented as a cleft cylinder occupying the interior, with the crystals of sulphate of copper piled up round it. The entire cylinder surrounding these is the porous partition, outside of which is the cleft cylinder of zinc Z, the whole being contained in a vessel of glass.

It is more usual in this country to dispense with the glass vessel, and interchange the places of the zinc and copper in the figure, the copper plate being a cylindrical vessel of copper containing the saturated solution. In this is immersed the porous vessel containing the other fluid with the zinc plate immersed in it. The cells thus constructed are usually arranged in square compartments in a wooden box.

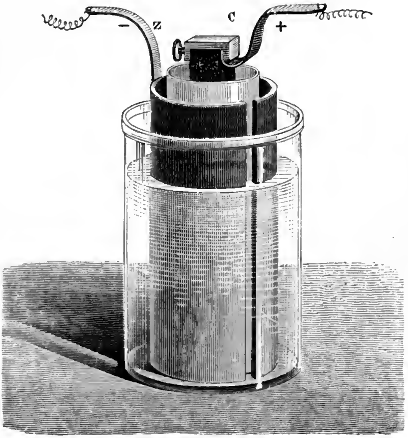


Fig. 457.—Bunsen's Cell.

706. Bunsen's Battery.—The battery which is now perhaps most extensively used for class experiments is that which was invented by Bunsen in 1843, being substantially identical with one previously invented by Grove, except that carbon is substituted for platinum.

The usual construction of its cells is very clearly represented in Fig. 457, and the mode of connecting them in Fig. 458. The cleft cylinder is the zinc plate, which is immersed in dilute sulphuric acid. Within this is the porous

cylinder, similar to Daniell's, containing *strong nitric acid,* in which is immersed a rectangular prism, of a very dense kind of charcoal, obtained from the interior of the retorts at gas-works, being deposited there in the manufacture of gas.

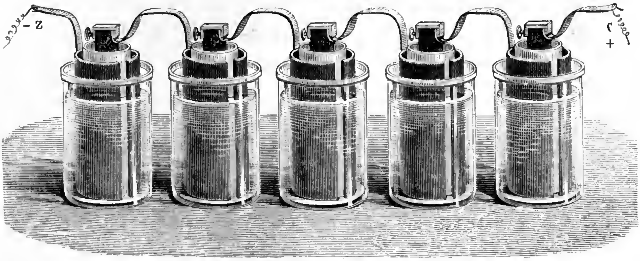


Fig. 458.—Bunsen's Battery.

In this cell the hydrogen is intercepted on its way to the carbon plate by the nitric acid, with which it forms nitrous acid.

Grove's battery possesses some advantages over Bunsen's; but its first cost is much greater.

707. Amalgamated Zinc.—When the poles of a battery are insulated from one another, there ought to be no chemical action in the cells. Any action which then goes on is wasteful, and is an indication that unproductive consumption of zinc goes on when the current is passing, in addition to the consumption which is necessary for producing the current. This wasteful action, which is called *local action,* goes on largely when the zinc plates are of ordinary commercial zinc, but not when they are of perfectly pure zinc. In this respect amalgamated zinc behaves like pure zinc, and it is accordingly almost universally employed. The amalgamation, which must be often renewed in the case of a battery in constant use, is performed by first cleaning the zinc plates with dilute acid, and then rubbing them with mercury.

708. Dry Pile: Bohnenberger's Electroscope.—For telegraphic purposes in this country, a battery is very commonly employed in which sand or sawdust, moistened with acidulated water, separates the zinc and copper plates of each cell.

The other forms of battery which have been devised are exceedingly numerous, and new forms are continually being introduced.

A *dry pile*, built up on the general plan of Volta's moist pile, was devised by De Luc, and improved by Zamboni. In Zamboni's construction, sheets of paper are prepared by pasting finely laminated zinc or tin on one side, and rubbing black oxide of manganese on the other. Discs are punched out of this paper, and piled up into a column, with their similar sides all facing the same way, to the number of a thousand or upwards, and are well pressed together. The difference of potential between the two ends is sufficient to produce sensible divergence of the gold-leaves of an electroscope, but the quantity of electricity which can be developed in a given time is exceedingly small. *No pile or battery can generate a sensible current, except by a sensible consumption of its materials in the shape of chemical action.*

A very delicate gold-leaf electroscope was devised by Bohnenberger, consisting of a single leaf suspended between the two poles of a dry pile, which for this purpose is arranged in two columns connected below, so that the poles are at the summits. If their lower ends, which form the middle of the series, be connected with the earth, one pole will always have positive, and the other negative potential. A very slight charge, positive or negative, given to the gold-leaf by means of the knob at the top of the case, suffices to make it move to the negative or the positive pole.

708A. Bichromate Battery.—The most convenient cells for most class experiments are the bichromate of potash bottle-cells, one of which is represented in Fig. 458A. The liquid is a solution of bichromate of potash, with a little sulphuric acid added. In this liquid two flat plates of carbon are suspended, and between them is a flat plate of zinc, which can be slid up and down by means of a rod projecting through the top of the cell. It is slid up when not in use, and is then just clear of the liquid. By pushing it down (which can be done instantaneously), the cell is brought into full action, and as soon as the experiment is concluded the zinc should again be raised out of the liquid. The cell is not suited for long-continued work, but it gives powerful effects when only used for a few minutes at a time. It has the conveniences of great portability and of freedom from noxious fumes.

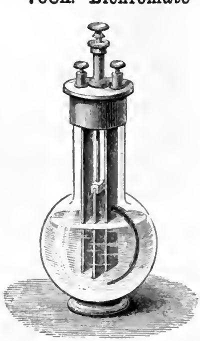


Fig. 458 A.—Bichromate Bottle-cell.

CHAPTER LIV.

GALVANOMETER.

709. Œrsted's Experiment.—The discovery by the Danish philosopher Œrsted, in 1819, that a magnetized needle could be deflected by an electric current, was justly regarded with intense interest by the scientific world, as affording the first indication of a definite relation existing between magnetism and electricity.

Œrsted's experiment can be repeated by means of the apparatus represented in Fig. 459. Two insulated metallic wires are placed in the magnetic meridian, one of them above, and the other below a magnetized needle. If a current be sent through one of these wires, the needle will be deflected; and if the current be strong, the deflection will nearly amount to a right angle. The direction of the deflection will be reversed if the current be passed through the lower instead of the upper wire. It will also be reversed by reversing the direction of the current. In the figure, the current is supposed to be passing above the needle from south to north. In this case the north end of the needle moves to the west, and the south end to the east. On making the current pass in various directions, either horizontally, vertically, or obliquely, near one pole of the needle, it will be found that deviation is always produced except when the plane containing the pole and current is perpendicular to the length of the needle.

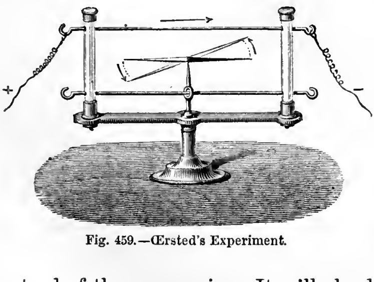


Fig. 459.—Œrsted's Experiment.

710. Ampère's Rule.—The direction in which either pole of a needle is deflected by a current, whatever their relative positions may be, is given by the following rule, which was first laid down by Ampère.

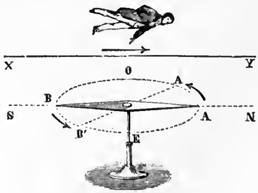


Fig. 460.

Ampère's Rule.

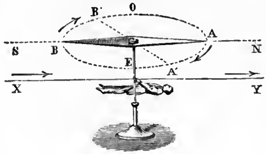


Fig. 461.

Imagine an observer to be so placed that the current passes through him, *entering at his feet* and leaving at his head, then the deflection of a *north-seeking pole* will be *to his left*. The deflection of a south-seeking pole will be in the opposite direction. The two figures 460, 461 illustrate the application of this rule to the two cases just considered. The current is supposed, in both cases, to be flowing from south to north. A is the austral or north-seeking pole of the needle, and B the boreal or south-seeking pole.

711. Lines of Magnetic Force due to Current.—The relation between currents and magnetic forces may be more precisely expressed by saying that a current flowing through a straight wire produces circular lines of force, having the wire for their common axis. A pole of a magnet placed anywhere in the neighbourhood of the wire, experiences a force tending to urge it in a circular path round the wire, and the direction of motion round the wire is opposite for opposite poles. Fig. 462 represents three of the lines of force for a north-seeking pole, due to a current flowing through a straight wire from the end marked + to the end marked −. The lines of force are circles (shown in perspective as ellipses), having their centre at a point C in the wire, and having their plane perpendicular to the length of the wire. The arrows indicate the direction in which a

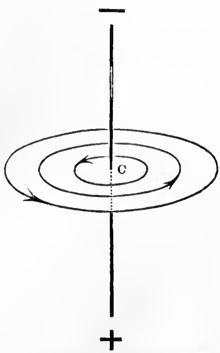


Fig. 462.—Lines of Force due to Current.

north-seeking pole will be urged. This direction is from right to left round the wire as seen from the wire itself by a person with his feet towards + and his head towards −, according to Ampère's rule. The figure may be turned upside down, or into any other position, and will still remain true.

712. Reaction of Magnet on Current.—While the wire, in virtue of the current flowing up through it, urges an austral pole from A towards A′ (Fig. 463), it is itself urged in the opposite direction C C′. If an observer be in imagination identified with the wire, the current being supposed, as in Ampère's rule, to enter at his feet, and come out at his head, the force which he will experience from a north-seeking pole directly in front of him will be a force to his right. It will be noted that the magnetic influence which thus urges him to the right, would urge a north-seeking pole from his front to his back. *A conductor conveying a current is not urged along lines of magnetic force, but in a direction which is at right angles to them, and at the same time at right angles to its own length.*

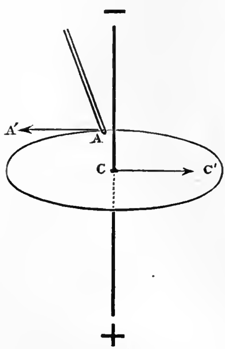


Fig. 463.—Reaction on Current.

713. Numerical Estimate of Currents.—The numerical measure of a current denotes the quantity of electricity which flows across a section of it in unit time. It is sometimes called *strength* of current, sometimes, especially by French writers, *intensity* of current, sometimes simply *current* or *amount* of current. If a thin and a thick wire are joined end to end, it has the same value for them both; just as the same quantity of water flows through the broad as through the contracted parts of the bed of a stream. Hence the name *intensity* is obviously inappropriate, for, with the same total quantity of electricity flowing through both, the current is, properly speaking, more *intense* in the thin than in the thick wire.

Currents may be measured experimentally by various tests, which are found to agree precisely. The most convenient of these for general purposes is the deflection of a magnetized needle. The force which a given pole experiences in a given position with respect to a wire conveying a current, is simply proportional to the current. Hence the name *strength* of current admits of being interpreted in a

sense corresponding to that in which we speak of the strength of a pole. Instruments for measuring currents by means of the deflections which they produce in a magnetized needle are called *galvanometers.*

714. Sine Galvanometer.—The sine galvanometer, which was invented by Pouillet, is represented in Fig. 464. The current which is to be measured traverses a copper wire, wrapped round with silk for insulation, which is carried either once or several times round a vertical circle; and this circle can be turned into any position in azimuth, the amount of turning being indicated on a horizontal circle. In the centre of the vertical circle, a declination needle is mounted, surrounded by a horizontal circle for indicating its position, this circle being rigidly attached to the vertical circle. Suppose that, before the current is allowed to pass, both the needle and the vertical circle are in the magnetic meridian, and that the needle consequently points at zero on its horizontal circle. On the current passing, the needle will move away. The vertical circle must then be turned until it overtakes the needle; that is, until the needle again points at zero. This implies turning the circles through an angle α equal to that by which the needle finally deviates from the magnetic meridian. In this position the terrestrial couple tending to bring back the needle to the meridian is proportional to $\sin \alpha$ (§ 679). The forces exerted upon the two poles by the current are perpendicular to the plane of the vertical circle, and are simply proportional to the current. Hence, in comparing different observations made with the same instrument, the amounts of current are proportional to the sines of the deviations.

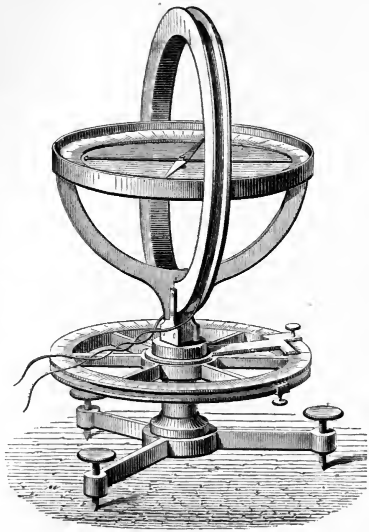


Fig. 464.—Sine Galvanometer.

715. Tangent Galvanometer.—The tangent galvanometer, which is simpler in its construction and use, and is much more frequently employed, consists of a declination needle mounted in the centre of a vertical circle whose plane always coincides with the magnetic meridian, the length of the needle being small in comparison with the radius of the circle.

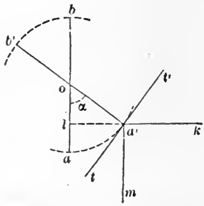


Fig. 465.—Principle of Tangent Galvanometer.

Let o (Fig. 465) be the centre of suspension, $a\,b$ the initial position of the needle, and $a'b'$ its deflected position. The force F exerted on either pole by the current is sensibly the same at a' as at a on account of the smallness of the needle, and it acts in the direction $l\,k$, while the horizontal force of the earth upon the pole acts along $a'\,m$; and these two forces give a resultant along $o\,a'$. Hence, taking the triangle $o\,l\,a'$ as the triangle of forces, the force exerted by the current is to the horizontal force exerted by the earth as $l\,a'$ to $o\,l$, or as $\tan\alpha$ to unity; that is, the current is proportional to the tangent of the deflection.

In order to permit the deviation of the short needle to be accurately read, a long pointer is attached to it, usually at right angles, the two ends of which move along a fixed horizontal circle.

716. Multiplier.—The idea of carrying a wire several times round a needle in a vertical plane is due to Schweiger. The form of apparatus designed by him, called *Schweiger's multiplier*, is represented in Fig. 466. The name *multiplier* is derived from the fact that, if the current is not sensibly diminished by increasing the number of convolutions of wire through which it has to pass, the force exerted on the needle is n times as great with n convolutions as with only 1, since each convolution exerts its own force on the needle independent of the rest.

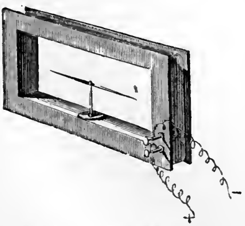


Fig. 466.—Schweiger's Multiplier.

Cases, however, frequently occur in which the increased *resistance* introduced by increasing the number of convolutions outweighs the advantage of multiplication, so that a short thick wire with few convolutions gives a more powerful effect than a long thin wire

with many. This is especially the case with thermo-electric currents.

The difference between the rectangular and the circular form is merely a matter of detail. Whichever form be adopted, all parts of the coil contribute to make the needle deviate in the same direction. For instance, in Fig. 467, if the current proceeds in the direction indicated by the arrows, the application of Ampère's rule to any one of the four sides of the rectangle shows that the austral pole a will be urged towards the front of the figure. When the coil is circular, and the needle so small that each pole is nearly in the centre, equal lengths of the current, in whatever parts of the circle they may be situated, exert equal forces upon the needle, and all alike urge the poles in directions perpendicular to the plane of the coil.

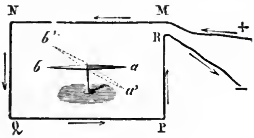


Fig. 467.

717. Differential Galvanometer.—The coil of a galvanometer sometimes consists of two distinct wires, having the same number of convolutions, and connected with separate binding screws. This arrangement allows of currents from two distinct sources being sent at the same time round the coil either in the same or in opposite directions. In the latter case, the resultant effect upon the needle will be that due to the difference of the two currents; and if they are not exactly equal, the direction of the deflection will indicate which of them is the greater. An instrument thus arranged is called a *differential galvanometer.*

718. Astatic Needle.—The sensibility of the galvanometer is greatly increased by employing what is called an *astatic* needle. It consists of a combination of two magnetized needles *with their poles turned opposite ways.* The two needles are rigidly attached at different heights to a vertical stem, and the system is usually suspended by a silk fibre, which gives greater freedom of motion than support upon a point. On account of the opposition of the poles, the directive action of the earth on the system is very feeble. If the magnetic moments of the two needles were exactly equal, the resultant moment would be zero, and the system would remain indifferently in all azimuths.

One of the needles $a\,b$ (Fig. 468) is nearly in the centre of the coil CDEF through which the current passes. The other $a'b'$ is just

above the coil. When a current traverses the coil in the direction of the arrows, the action of all parts of the current upon the lower needle tends to urge the austral pole a towards the back of the figure, and the boreal pole b to the front. The upper needle $a'b'$ is affected principally by the current in the upper part CD of the coil, which urges the austral pole a' to the front of the figure, and the boreal pole b' to the back. Both needles are thus urged to rotate in the same direction by the current, and as the opposing action of the earth is greatly enfeebled by the combination, a much larger deflection is obtained than would be given by one of the needles if employed alone.

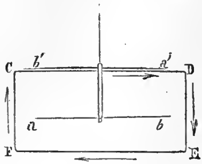


Fig. 468.

If the two needles had rigorously equal moments, the system would be said to be *perfectly astatic*. The smallest current in the coil would then suffice to set the needles at right angles to the meridian, and no measure would be obtained of the amount of current.

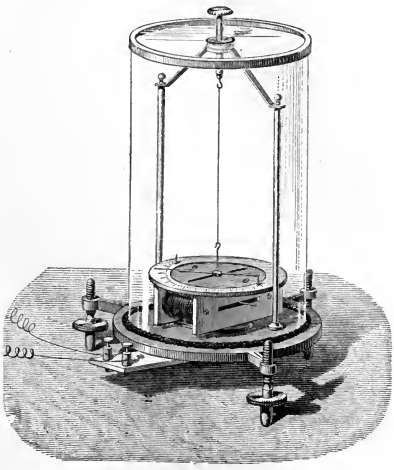


Fig. 469.—Astatic Galvanometer.

Fig. 469 represents an astatic galvanometer, as usually constructed. The coil is wound upon an ivory frame, which supports the divided circle in whose centre the upper needle is suspended. The ends of the coil are connected with two binding screws, for making connection with the wires which convey the current to be measured. The needles are usually two sewing-needles, and the upper one often carries a light pointer. The suspending fibre is attached at its upper end to a hook, which can be raised or lowered, and when the instrument is not in use this is lowered till the upper needle

rests upon the plate beneath it, so as to relieve the fibre from strain. In using the instrument care must be taken to adjust the three levelling-screws so that the needle swings free.

719. Thomson's Mirror Galvanometer.—The most sensitive galvanometer as yet invented is the mirror galvanometer of Sir W. Thomson. Its needle, which is very short, is rigidly attached to a small light concave mirror, and suspended in the centre of a vertical coil of very small diameter by a silk fibre. A divided scale is placed in a hori-

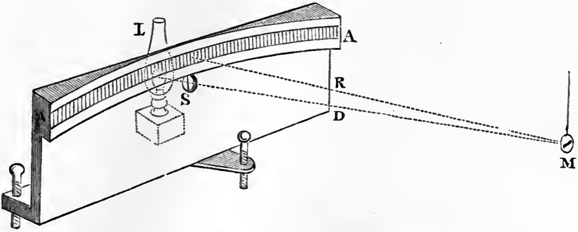


Fig. 470.—Mirror and Scale.

zontal position in front of the mirror, at the distance of about a yard, and the image of an illuminated slit, which is thrown by the mirror upon this scale, serves as the index. The arrangement of the mirror and scale, which is the same as in the case of the quadrant electrometer described in a previous chapter, is exhibited in Fig. 470. M is the mirror of silvered glass, slightly concave, with a small piece of magnetized watch-spring attached to its back, the two together weighing only a grain and a half, and suspended by a few fibres of unspun silk. AA is a divided scale forming an arc of a horizontal circle about the mirror as centre. Immediately below the centre of this scale is a circular opening S with a fine wire stretched vertically at the back of it. A paraffine lamp L is placed directly behind this opening, so as to shine through it upon the mirror, which is at such a distance as to throw upon the screen a bright image of the opening with a sharply-defined dark image of the wire in its centre. The image of the wire is employed as the index in taking the readings.

In order to obviate the necessity of keeping the needle in the meridian, with the lamp east or west of it, and to admit of other positions which may be more convenient, a magnet M (Fig. 471) is

provided which can be raised or lowered, and can also be turned round. When it is low down it overpowers the earth's magnetism, and compels the needle to take any position that may be required.

For maximum sensitiveness, the magnetic field around the needle should be made as weak as possible. For this purpose the needle should be placed in or not far from the meridian, and the magnet, after being turned into such a position as directly to oppose the earth's action on the needle, should be raised or lowered till its force is a very little less or greater than that of the earth. The operator in making the adjustment watches the vibrations of the needle, as indicated by the movements of the image on the scale, and knows that the force on the needle is diminishing when he sees the vibrations becoming slower.

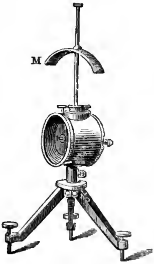


Fig. 471.—Thomson's Mirror Galvanometer.

For use at sea the galvanometer is modified by fastening the supporting fibre of silk at both ends, so as to keep it tight, with the needle and mirror attached at its centre, care being taken to make the direction of the fibre pass through the common centre of gravity of the needle and mirror, in order that the rolling of the ship may not tend to produce rotation. In this form it is called the *marine galvanometer.*

720. Calibration of Galvanometer.—The deviations of the needle of a galvanometer, when large, are not proportional to the currents which produce them. In order to be able to translate the indications of the instrument into proportional measure, a preliminary investigation must be made, and its results embodied in a table. This has been done in several ways. We shall merely indicate the method employed by Melloni for deducing from the deflections of his galvanometer the amounts of heat received by his thermo-pile.

He placed two sources of heat opposite the two ends of the pile, and allowed them to radiate to it, first one at a time, and then both together. One of them produced a deviation, say of 5°, and the other of 10°, and when the two were acting jointly the deviation was 5°. Since the latter number is the difference of the other two, the inference is that up to 10° the deflections are proportional to the amounts of heat received. Melloni thus established that the proportionality subsisted up to 20°. When the two sources separately produced deflections of 20° and 25°, and a deflection of 6°·5 jointly, he inferred

that a deflection of 25° indicated an amount of heat represented by 26°·5; for the heat which produced the deflection of 25° was the sum of the two amounts represented separately by 20° and 6°·5. By a succession of steps of this kind, the calibration (as this process is called[1]) can be extended nearly to 90°.

This mode of investigation covers any want of proportionality which may exist in the production of thermo-electric currents, as well as in the proportionality of these currents to the deflections.

721. General Law for Magnetic Force due to a Current.—In every case, the magnetic force at a given point due to a current, can be computed by dividing the current into elementary portions, each sensibly straight, and compounding by the parallelogram of forces the effects due to these separate elements. The force due to each element is normal to the plane drawn through the element and the given point, and is proportional to $C\frac{l}{r^2}\sin\theta$, where C denotes the strength of the current, l the length of the element, r the distance between the element and the given point, and θ the angle between the joining line and the element. The force at the centre of a single circular current of radius a is therefore $C\frac{2\pi a}{a^2} = C\frac{2\pi}{a}$, and the force at the centre of a circular galvanometer-coil of n convolutions, if all can be regarded as in one plane and of the same radius a, is $C\frac{2\pi n}{a}$.

When a galvanometer needle is deflected, it is no longer in the plane of the coil, and this circumstance complicates the relation between current and deflection. Helmholtz has overcome this difficulty by placing the needle midway between two equal and parallel coils, whose distance apart is equal to the radius of either, the two being connected in series so that the same current flows through both. The lines of magnetic force in the intervening region can be shown to be very nearly straight.[2]

722. Effect of Instantaneous Current.—When the duration of a current is small in comparison with the time of vibration of the needle, and the total deflection small, the velocity which the current gives the needle is jointly proportional to the duration of the current and its average strength. It is, therefore, simply proportional to the

[1] From its analogy to the calibration of a thermometer.

[2] A drawing of the lines will be found in Maxwell's *Electricity and Magnetism*, vol. ii. fig. xix.

quantity of electricity which passes. This velocity is equal to that acquired in the return movement to zero; and this latter obviously follows the same law as the motion of a simple pendulum, for in both cases the effective force is proportional to the sine of the displacement. In the case of the pendulum, the square of the velocity acquired in the whole descent is proportional to the vertical height descended, and this vertical height multiplied by the diameter of the circle in which the pendulum moves, is equal to the square of the chord; hence, the velocity acquired is proportional rigorously to the chord, and approximately to the arc of descent if small. The same rule must hold for the needle; that is to say, the velocity acquired must be proportional to the extreme displacement. *The quantity of electricity transmitted through the galvanometer coil by an instantaneous discharge is* therefore *proportional to the distance to which the needle swings.*

723. The Galvanometer a True Measurer of Current.—This reasoning assumes the principle that the force exerted by a current on a needle is a true measure of the strength of the current (defined as the quantity of electricity conveyed per unit of time); and conversely, the observed fact that, when known quantities of electricity are discharged through a galvanometer, the swings produced are proportional to these quantities, establishes the principle. The experiment has frequently been made by discharging a condenser (§ 628) which has been charged by a galvanic battery; and Faraday obtained a similar result with Leyden-jars which had been charged by a powerful frictional machine, the jars being discharged through a wet thread or string leading to the galvanometer. He found that the swing was independent of the length and thickness of the thread or string, as well as of the number of jars employed, and was proportional to the number of turns that had been given to the electrical machine in charging the jars.

The proportionality of force to current might have been inferred *à priori* from the consideration that, if we have two parallel wires close together, conveying equal currents, the resultant force on a pole will be the sum of the forces due to each, and will therefore be double of the force due to one alone. The force will not be altered by allowing the wires to touch each other all along their length; and in this position they form a single conductor conveying a double current.

724. Needle Deflected by Motion of a Charged Body.—The question

has been raised whether the carrying of electricity by the motion of a charged body produces effects similar to those of a current flowing through a conductor, and in particular, whether it is capable of deflecting a magnetized needle. The matter has been put to the test by Professor Rowland of Baltimore, in an experiment performed at the laboratory of the Berlin University.[1]

The carrier of the electricity was a rapidly revolving horizontal disc of ebonite, gilt on both sides, and maintained in a high state of electrification by means of a fixed discharging point connected with one of the coatings of a battery of Leyden-jars. The needle to be deflected was suspended over it near its circumference, the length of the needle being perpendicular to the radius of the disc, so that the motion of the electricity beneath the needle was parallel to its length. Between the needle and the revolving disc, a larger fixed disc of glass, gilt on one side and connected with the earth, was interposed; and there was a similar disc on the lower side. The needle was one of an astatic pair, the other needle being at a much greater height; and both were inclosed in a brass case, to protect them from electrostatic influences. The deflection was observed by means of a mirror attached to the stem of the needles, and a telescope for viewing in the mirror the reflected image of a scale. The disc, which was $8\frac{1}{3}$ inches in diameter, revolved at the rate of about 60 turns per second, and the deflections observed amounted to from 5 to $7\frac{1}{2}$ divisions of the scale, the deflection being to the one side or the other, according as the charge of the disc was positive or negative. The observations extended over several weeks, and conclusively proved, subject to small errors of observation and reduction, that the magnetic effect of carrying a charge of electricity is the same as that of the flow of the same quantity of electricity in the same time through a conductor.

[1] See *Phil. Mag.* September, 1876, pp. 211–216.

CHAPTER LV.

ELECTRO-CHEMISTRY.

725. Electrolysis.—When a current is passed through a compound liquid, decomposition is frequently observed, two of the component substances being separated, one at the place where the current enters and the other at the place where it leaves the liquid. This decomposition is called *electrolysis,* and the substance decomposed or *electrolysed* is called the *electrolyte.* The action only occurs in the case of liquids, and these must be conductors.

The process may be illustrated by the decomposition of water as represented in Fig. 472. The apparatus consists of a vessel con-

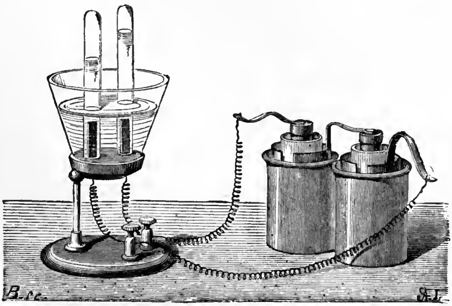


Fig. 472.—Voltameter.

taining water to which a little sulphuric acid has been added, and in which two strips of platinum are immersed, connected respectively with the two poles of a battery. When the connections are completed, bubbles make their appearance at the surfaces of the two

strips and rapidly rise to the surface. If two tubes filled with the liquid are inverted over the two strips, the gases will bubble up through the liquid into the upper part of these tubes and the level of the liquid will gradually fall as shown in the figure. It will be found that the volume of the hydrogen is about double that of the oxygen.

The two strips of platinum are called the poles or *electrodes* of the decomposing cell; the one in connection with the positive pole of the battery is called the *anode* (literally the *way up*) and the one in connection with the negative pole the *cathode* or *kathode* (*way down*). The direction of the current through the liquid is from the anode to the kathode. The gas which is given off at the anode (in the present case oxygen) is called the *anion* (*that which goes up*) and that which is given off at the kathode the *kathion* or *cation* (*that which goes down*). The anion is often called the *electro-negative* element, because it moves as if attracted by the positive and repelled by the negative pole. For a similar reason the kathion is called the *electro-positive* element.

In many cases, the separation effected by the direct action of the current is followed by secondary actions due to chemical affinities.

Thus, in the decomposition of acidulated water above described, the first effect, according to modern theory, is a breaking up of the sulphuric acid ($S\,O_3$, $H_2\,O$) into hydrogen and sulphion (2 H and $S\,O_4$), the latter being a substance which has never been obtained by itself. The hydrogen travels to the negative pole and there escapes. The sulphion goes to the positive pole, but instead of escaping enters into combination with the hydrogen of the liquid, forming again the primitive compound ($S\,O_3$, $H_2\,O$) and leaving the oxygen of the liquid to escape.

726. Transport of Elements.—It is a remarkable fact that the separated elements never make their appearance except at the electrodes. Nothing is seen of them, nor is any action exhibited, at intermediate points. The appearance is as if the gases could vanish from one extremity and appear at the other without passing through the intermediate space. The only possible explanation of this phenomenon seems to be what is known as Grotthus'

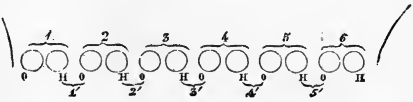


Fig. 473.—Grotthus' Hypothesis.

hypothesis, that all the particles of the water in the course of the current undergo continual decomposition and recomposition. Thus if Fig. 473 represent a line of particles traversed by the current from left to right, there will be a continual stream of hydrogen particles along this line from left to right, and a stream of oxygen[1] particles from right to left. The hydrogen of molecule 1 will combine with the oxygen of molecule 2 to form a new molecule 1′; the hydrogen of molecule 2 will combine with the oxygen of molecule 3 to form a new molecule 2′, and so on. The oxygen of molecule 1 is given off at the left-hand extremity, which we suppose to be the point of contact with one of the strips of platinum, and the hydrogen of molecule 6 at the other strip. The molecules 1′, 2′, 3′ . . . are then in their turn decomposed to form a new set. In actual cases, the number of molecules, instead of being only six as represented in the figure, is of course many millions.

727. Discovery of Potassium.—When a compound formed by the union of a metal with a non-metallic substance is submitted to electrolysis, the metal always comes to the negative pole. It was in this way that several of the metals were first obtained from their oxides by Sir Humphry Davy. Potassium, for example, was obtained by placing a piece of potash on a platinum disc connected with the negative pole of a battery of 250 cells, and then applying a platinum wire connected with the positive pole to its upper surface. The potash, which had been allowed to contract a little moisture from the atmosphere, in order to give it sufficient conducting power, soon began to fuse at the points of contact of the electrodes. A violent effervescence occurred at the upper or positive electrode; while at the lower surface small globules appeared resembling quicksilver, some of which instantly burst into flame, while others merely became tarnished and afterwards coated over with a white film.

728. Electrolysis of Salts.—When a salt of any of the less inflammable metals is submitted to electrolysis, a continual deposition of the metal is observed on the negative electrode; while, at the positive electrode, oxygen is disengaged, and acid set free. These effects occur, for example, if platinum electrodes are plunged in a solution of sulphate of copper. If copper is employed as the positive electrode, the oxygen will combine with it instead

[1] Or sulphion particles according to modern theories. The explanation as it stands in the text represents the views held by Faraday and his contemporaries.

of being given off, and the oxide thus formed will be dissolved by the acid.

729. Voltameters.—The quickness with which a given electrolyte is decomposed is simply proportional to the strength of the current; and any apparatus designed for measuring the strength of a current on this principle is called a *voltameter*. The apparatus in Fig. 472 is one of its forms. The commonest form consists of a cell containing a solution of sulphate of copper, with two copper plates for electrodes. As the current passes, the anode is gradually dissolved away, and an equal quantity of copper is deposited on the kathode. The quantity of electricity that has passed through the cell can accordingly be determined by weighing the plates. Copper, however, has the drawback that it is to some extent acted on by the solution when no current is passing. When the greatest possible accuracy is required, two plates of silver immersed in a solution of nitrate of silver are preferred.

730. Quantitative Laws of Electrolysis.—The following table gives, in the column headed "chemical equivalent," the quantities of the several elements deposited by one and the same quantity of electricity. It will be seen from the table that the same element in different states of combination may have different equivalents. The general law for such cases is that the equivalent is equal to the atomic weight (which is definite for each element) divided by the "valency." The "valency" expresses the number of atoms of hydrogen which are replaced by one atom of the substance.

	Atomic weight.	Valency.	Chemical equivalent.
Electro-positive.			
Hydrogen,	1	1	1
Potassium,	39·1	1	39·1
Sodium,	23·	1	23·
Gold,	196·6	3	65·5
Silver,	108·	1	108·
Copper (Cupric),	63·	2	31·5
„ (Cuprous),	63·	1	63·
Mercury (Mercuric),	200·	2	100·
„ (Mercurous),	200·	1	200·
Tin (Stannic),	118·	4	29·5
„ (Stannous),	118·	2	59·
Iron (Ferric),	56·	3	18·7
„ (Ferrous),	56·	2	28·
Nickel,	59·	2	29·5
Zinc,	65·	2	32·5
Lead,	207·	2	103·5
Aluminium,	27·	3	9·

	Atomic weight.	Valency.	Chemical equivalent.
Electro-negative.			
Oxygen,	16·	2	8·
Chlorine,	35·5	1	35·5
Iodine,	127·	1	127·
Bromine,	80·	1	80·
Nitrogen,	14·	3	4·3

The quantity of a substance that is deposited by the passage of a unit of electricity is called the *electro-chemical equivalent* of the substance. The electro-chemical equivalent of sil·er, according to the latest and best determinations, is ·01118 of a gramme for one C.G.S. unit of electricity, or ·001118 of a gramme for one "coulomb." The electro-chemical equivalents of the other substances mentioned in the above table can be calculated from this by simple proportion.

The above table holds good also for battery cells, provided that there is no wasteful "local action." The quantity of zinc dissolved in each cell of a battery is chemically equivalent to the quantity of any metal that is deposited in an electrolytic cell by the same current.

731. Chemical Relations of Electro-motive Force.—The energy of the current produced by a battery is equal to the potential energy of chemical affinity which runs down in its production; and this latter is measured by the heat of combination due to the chemical action which goes on in the battery. If there are decomposing cells in circuit, they contribute negative heat of combination, and there can be no current unless the total heat of combination for the whole circuit be positive.

The energy of the current for a given time is equivalent to the total heat of combination due to the action which takes place in this time; and if this energy be divided by the quantity of electricity conveyed by the current in the time, the quotient is called the *electro-motive force* of the circuit.

The quantity of electricity conveyed bears a definite relation of equivalence to the zinc dissolved in any one cell; and hence the electro-motive force of a cell is proportional to the heat of combination due to the action which takes place during the consumption of a given quantity of zinc. This heat is about twice as great for a Grove's cell as for a Daniell, and hence the electro-motive force of the former is about double that of the latter.

732. Secondary Batteries.—We have stated in § 704 that in some

forms of battery a reverse electromotive force is produced by the deposition of gas on the surface of the plates, and that this action is called *polarization*. A similar effect occurs in the voltameter of Fig. 472; and if the oxygen and hydrogen, as they are given off, are collected in separate tubes, each platinum plate being in contact both with one of the gases and with the liquid, the voltameter, after being disconnected from the source of the original current, can be used as a battery cell giving a current in the opposite direction. This is the principle of *Grove's Gas Battery*, in which the tubes may be filled with oxygen and hydrogen either by electrolysis or in any other manner, and any number of the cells may be connected in series. During the flow of the current which this battery gives, the two gases of each cell gradually unite through the medium of the acidulated water between them.

Any cell which is first subjected to electrolysis by a current from an external source, and then gives of itself a current in the opposite direction, is called a *secondary cell*, and a combination of such cells is a *secondary battery*. Recent improvements in their construction have called public attention to them as an important means of storing up energy, to be used when and where it is wanted. Hence they have received the name of *storage batteries* or *accumulators*.

733. Faure's Accumulator.—Faure's Accumulator consists of two leaden plates of large surface, covered with minium (red oxide of lead), rolled up together with flannel between them, and immersed in dilute sulphuric acid. The primary current, which is usually supplied by a dynamo machine, changes a portion of the minium on the anode into peroxide of lead, and reduces a portion of the minium on the cathode to metallic lead in a spongy condition. It is probably to the presence of these two substances with dilute sulphuric acid between them, that the secondary current is due. A battery of these cells freshly charged by a dynamo machine will give a powerful current for some hours; and an interval of a few hours or even of a few days between charging and using does not involve very much loss.

Planté had previously constructed secondary cells consisting in like manner of two lead plates spirally coiled in dilute sulphuric acid, and had greatly improved their action by coating them with peroxide, which he did, not by mechanical means, but by sending through the cell a succession of currents in opposite directions, with intervals of rest between.

Planté has also constructed a "rheostatic machine" containing some hundreds of these cells each connected to a separate condenser, and with an arrangement by which the connections of the cells can be instantaneously altered. During the charging process, poles of the same name in the secondary cells are all connected together, one set being connected with the positive pole of the charging battery, and the other set with the negative pole, the charging battery being usually composed of two large Bunsen cells. A small movement suffices to alter the connections so as to arrange the secondary cells in series, and a battery is thus obtained whose electro-motive force is hundreds of times greater than that of the charging battery. The process of charging is instantaneous, and a quick succession of discharges of the secondary battery can be obtained by turning a handle, the effects being somewhat similar to the discharges of a Ruhmkorff coil (§ 815).

734. Applications of Accumulators.—Accumulators serve two important purposes. They can be used either like a fly-wheel, to smooth down irregularities in the supply of energy, or, like a mill-reservoir, to store up a large quantity of energy which is running to waste, and give it out later.

For example, a gas-engine usually gives alternately a quick stroke and a slow one; and when it is employed to drive a dynamo for supplying incandescent lamps, a corresponding flickering is seen in the lamps. This evil can be effectually cured by connecting the two terminals of the dynamo with the two terminals of a storage battery. The battery, after it has been charged up to a certain point, absorbs energy during each quick stroke, and gives it out again during the slow stroke, thus keeping the electro-motive force of the main circuit nearly constant.

On the other hand, storage cells can be charged during the day by employing the surplus power of a factory engine to drive a dynamo, and can be used at night to supply electricity for lighting the factory. Or they can be charged by a dynamo driven by a fixed engine, and can then be placed in a tram-car to supply motive power for its journey.

735. Electro-metallurgy.—The applications of electrolysis to the arts are numerous and important. They are of two kinds. In one, the electrolytic deposit is intended as a permanent covering, and should adhere perfectly so as to form one mass with the body which it covers. In the other, the adhesion is temporary, and must not be

too close, the object being merely to obtain an exact copy of the original form. Electro-plating belongs to the former class; electrotype to the latter.

736. Electro-gilding and Electro-plating.—The deposition of a coating of gold or silver on the surface of a less precious metal is merely an example of the electrolysis of a salt, as described in § 728. The metal in solution is always deposited on the negative electrode; hence we have merely to make the negative electrode consist of the article which we wish to coat. The only points to be decided practically relate to the means of making the deposit solid and firmly adherent. These ends have been completely attained by the methods patented about 1840 by Elkington in England and Ruolz in France.

The solutions are always alkaline, and usually consist of the cyanide or chloride of the metal, dissolved in an alkaline cyanide.

To prepare the *gold bath*, 50 grammes of fine gold are dissolved in aqua regia; and the solution is evaporated till it has the consistence

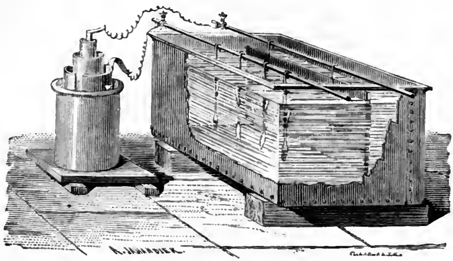


Fig. 476.—Apparatus for Electro-gilding.

of syrup. Water is then added, together with 50 grammes of cyanide of potassium, and the mixture is boiled. The quantities named give about 50 litres of solution.

The negative electrode consists of the article to be gilded. The positive electrode is a plate of fine gold, which constitutes a soluble electrode, and serves to keep the solution at a constant strength. In order that the gilding may be well done, the bath must be maintained, during the operation, at a temperature of from 60° to 70° Centigrade.

Fig. 476 represents a form of apparatus which is very frequently

employed. The poles of the battery are connected with two metallic rods resting on the top of the cistern which contains the bath. The articles to be gilded are hung from the negative rod. From the positive rod is hung a plate of gold, whose size should be proportional to the total surface of the articles which form the negative electrode.

The *silver bath* is a solution containing 2 parts of cyanide of silver, 10 of cyanide of potassium, and 250 of water. The operation of plating is the same as that of gilding, except that the apparatus is usually on a larger scale, and that the temperature may be lower.

In both cases the surfaces to be coated must be thoroughly cleansed from grease. For this purpose they are subjected to the processes of pickling and dipping, which we cannot stay to describe.

Other bodies, as well as metals, can be coated, if their surfaces are first covered with some conducting material. Baskets, fruits, leaves, &c., have thus been gilded or silvered.

Similar processes are employed for depositing other metals, of which copper is the most frequent example.

737. Electrotype.—Electrotyping consists in obtaining copper casts or fac-similes of medals, engraved plates, &c., by means of electrolytic

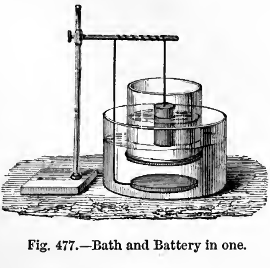


Fig. 477.—Bath and Battery in one.

deposition. The first successful attempts in this direction were made about 1839 by Jacobi at St. Petersburg and Spencer in England. The art is now very extensively practised.

If a fac-simile of a medal is required, a cast is first taken of it, either in fusible alloy, plaster of Paris, or gutta percha softened by heating to 100° C., this last material being the most frequently employed. The fusible alloy is a conductor; the other materials are not, and their surfaces are therefore rendered conducting by rubbing

them over with plumbago. The mould thus prepared is made to serve as the negative electrode in a bath of sulphate of copper, a copper plate being used as the positive electrode. When the current passes, copper is deposited on the surface of the mould, forming a thin sheet, which, when detached, is a fac-simile of one side of the original medal. A similar process can be applied to the other side, and thus a complete copy can be obtained.

In operations of this kind, the bath itself is often made to serve as the battery. Fig. 477 represents such an arrangement.

In the interior of a vessel containing a saturated solution of sulphate of copper, a second vessel is supported, consisting either of porous earthenware or of a glass cylinder closed below by a membrane. In this second vessel is placed acidulated water, with a cylinder of zinc suspended in it. The mould is placed in the outer vessel under the bottom of the porous cylinder, and is connected with the zinc by a stout wire which completes the circuit. The arrangement is evidently equivalent to a Daniell's cell. The current passes through the liquids from the zinc to the mould, electrolysing the solution of sulphate of copper; and as the metal travels with the current, it is deposited on the surface of the mould. The strength of the solution is kept up by suspending in it crystals of sulphate of copper contained in a vessel pierced with holes.

738. Applications of Electrotype.—One of the commonest applications of electrotype is to the production of copies of wood engravings. The original blocks, as they leave the hand of the engraver, could not yield a large number of impressions without being materially injured by wear. When many impressions are required, they are not taken directly from the wood, but from an electrotype taken in copper from a gutta-percha mould. The process of deposition is continued only for twenty-four hours, and the plate of copper thus obtained is very thin. It is strengthened by filling up its back with melted type-metal. Such plates will afford about 80,000 impressions, and it is from them that nearly all the illustrations in popular works are printed. Postage stamps, which must be exactly alike in order to prevent counterfeits, are also printed from electrotypes; and, on account of the great number of impressions required, the electrotypes themselves need frequent renewal; but the operations necessary for this purpose do not sensibly injure the original.

Copperplate engravings and even daguerreotypes can be very accurately reproduced in copper. No preparation of the surface is

necessary, as the thin film of oxide which is present is quite sufficient to prevent the deposit from adhering too closely.

Gasaliers are usually of cast-iron coated with copper by electrolysis. The copper is not, however, deposited on the surface of the iron, as the contact of the two metals would greatly promote the oxidation of the iron, if any of it were accidentally exposed to the air. The iron is first painted over with red-lead, which, when dry, is covered with a very thin layer of plumbago to render it conducting; and it is on this that the copper is deposited.

CHAPTER LVI.

OHM'S LAW.

739. Statement of Ohm's Law.—The strength of the current which traverses a circuit depends partly on the electro-motive force of the source of electricity, and partly on the resistance of the circuit. For equal resistances, it is proportional to the whole electro-motive force tending to maintain the current, and for equal electro-motive forces it is inversely as the whole resistance in the circuit. Hence, when proper units are chosen for expressing the current C, the resistance R, and the electro-motive force E, we have

$$C=\frac{E}{R},$$

or *the current is equal to the electro-motive force divided by the resistance.* This is Ohm's law, so called from its discoverer.

740. Explanation of the term Electro-motive Force.—We have already (§ 734) defined electro-motive force as the quotient of the energy of a current by the quantity of electricity which it conveys. This definition implies that electro-motive force is a quantity of the same nature as difference of potential; for when electricity passes from one conductor to another, the work done in the passage is equal to the quantity of electricity multiplied by the difference of potentials of the two conductors.

When a steady current is flowing through a galvanic circuit, there must be a gradual fall of potential in every uniform conductor which forms part of the circuit; since, in such a conductor, the direction of a current must necessarily be from higher to lower potential. These gradual falls are exactly compensated by the abrupt rises (diminished by the abrupt falls, if any) which occur at the various places of contact of dissimilar substances. Recent experiments by Sir W. Thomson seem to prove that by far the most important of

these abrupt transitions occur at the junctions of dissimilar metals, a view which was originally propounded by Volta, who appears, however, to have overlooked the essential part played by chemical combination in supplying the necessary energy.

If we imagine a large and deep trough of water of annular form, divided into compartments by transverse partitions; and suppose a constant difference of level to be maintained on opposite sides of each partition, by steady pumping of water from each compartment to the next; we have a rough representation of the distribution of potential in the cells of a battery; the rise of level in passing across a partition being analogous to the rise of potential in traversing a metallic junction.

The electro-motive force of a galvanic battery may be defined as the *algebraic sum of the abrupt differences of potential which occur at the junctions of dissimilar substances.* In a battery consisting of a number of similar cells arranged in series, it is of course proportional to the number of cells.

741. Explanation of the term Resistance.—When the current of a circuit is taken through the coil of a galvanometer, it is found that, by introducing different lengths of connecting wire, very different amounts of deflection can be obtained. The longer the wire which connects either pole of the battery with the galvanometer, the smaller is the deflection; and a small deflection indicates a feeble current. The current is in like manner weakened by introducing a fine instead of a stout wire, if their length and material be the same, or by introducing an iron wire instead of a copper wire of the same dimensions. These differences in the properties of the different wires are expressed by saying that they have different resistances.

It is found that, to produce no change in the deflection, the length of the wire must vary directly as its cross-section; that is to say, if l, l', l'' . . . . be the lengths of different wires employed, and s, s', s'' . . . . their sectional areas, their resistances will be equal, if

$$\frac{l}{s}=\frac{l'}{s'}=\frac{l''}{s''} \cdots\cdot$$

This is on the supposition that the wires are all of precisely the same material. Every substance has its own specific resistance, the reciprocal of which is its electrical conductivity and is precisely analogous to thermal conductivity. Denoting specific resistances by r, r', r'', ... the condition of equal resistances, when the materials are different, is

$$\frac{rl}{s}=\frac{r'l'}{s'}=\frac{r''l''}{s''}\ldots.$$

and the resistance of any wire is expressed by the formula $\frac{rl}{s}$, l denoting its length, s its sectional area, and r the specific resistance of its material.

To express, in terms of the equivalent length of one wire, the resistance of a circuit composed of several, we can employ the relation

$$\frac{rl}{s}=\frac{r'l'}{s'}; \text{ whence } l=\frac{s}{s'}\frac{r'}{r}l',$$

l denoting the length of one kind of wire equivalent to the length l' of the other. The length l is called the reduced length of the wire whose actual length is l'.

742. Rheostat.—Wheatstone's *rheostat* was one of the earliest instruments contrived for the comparison of resistances. It consists (Fig. 478) of two cylinders, one of brass, and the other of non-conducting material, so arranged that a copper wire can be wound off the one on to the other by turning a handle. The surface of the non-conducting cylinder B has a screw-thread cut in it, for its whole length, in which the wire lies, so that its successive convolutions are well insulated from each other. Two binding-screws are provided for introducing the rheostat into a circuit; and the resistance which is thus introduced depends on the length of wire which is wrapped upon the non-conducting cylinder, for the brass cylinder A has so large a section that its resistance may be neglected. The amount of resistance can thus be varied as gradually as we please by winding on and off. The handle can be shifted from one cylinder to the other. The figure shows it in the position for winding wire off A on to B. The number of convolutions of wire on B can be read off on a graduated bar provided for the purpose, and parts of a revolution are indicated on a circle at one end.

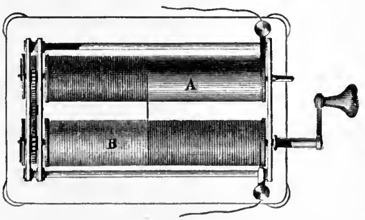


Fig. 478.—Rheostat.

Fig. 479 represents a very direct mode of measuring resistances

by the rheostat. The current traverses a galvanometer B, a rheostat R, and the conductor *m*, whose resistance is to be measured, the whole of the wire of the rheostat being wound on the brass cylinder. The deflection of the galvanometer having been observed, the conductor *m* is taken out of circuit, the two wires at *a* and *b* are directly connected, and as much of the rheostat wire is brought into circuit as suffices to reduce the deflection to its former amount.

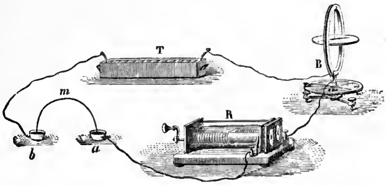


Fig. 479.—Measurement of Resistance.

743. Resistance Coils.—Measurements of resistance are now usually made by comparison with standard coils of wire which at a certain specified temperature have known resistances. The most usual material for the wire is German silver, this being a metal whose resistance is comparatively little affected by temperature. An alloy of platinum and silver is also frequently used, for the same reason. The coil is always wound double, as in Fig. 480, because this arrangement prevents it from influencing or being influenced by magnets and currents in the neighbourhood. In fact, the influences exerted or received by the two strands of the coil cancel one another.

The coils are usually fixed in a box in such a manner that, by

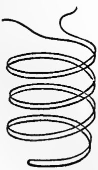


Fig. 430.—Resistance Coil.

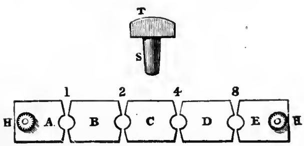


Fig. 481.—Mode of Connecting Resistance Coils.

combining separate coils, resistances of 1, 2, 3 or any integer number of *ohms* up to 5000 or 10,000 can be obtained. The mode of combining them will be understood by reference to Fig. 481.

A, B, C, D, E are stout plates of brass, which can be connected together by the insertion of plugs in the hollows between them. The plugs (one of which is shown in the figure) are of brass, with

ebonite handles, and exactly fit the hollows, so as to give contact over a large surface. The ends of one coil are attached to A and B, the ends of the next to B and C, and so on, the resistances of the coils being marked in figures above them. When the hollow between two plates is open, the current can only pass from one to the other by going through the intervening coil; but when the plug is inserted the resistance between the plates is inappreciable.

Hence the resistance between the two binding-screws H, H, attached to the extreme plates, will be the sum of the unplugged resistances.

744. Specific Resistances and Conductivities.—Numerous experimenters have compared the specific resistances of the different metals. Though the results thus obtained exhibit some diversity, they all agree in making silver, gold, and copper the three best conductors. Slight impurities, especially in the case of copper, have a very great effect in diminishing conductivity, or, in other words, in increasing resistance. Resistance is also increased, in the case of metals, by increase of temperature; but the opposite rule holds for insulators, such as gutta-percha and india-rubber. Their electrical resistance diminishes as the temperature increases.

Forbes has pointed out that the order of the metals as regards their conductivity for heat is the same as for electricity. The effects of impurity and of change of temperature are also alike in the two cases, as has been shown by Professor Tait.

The following are E. Becquerel's determinations of specific electrical resistance at the temperature 15° C., the resistance of silver at 0° C. being denoted by 100:—

SPECIFIC RESISTANCES AT 15° C.

Silver,	107	Palladium,	715
Copper,	112	Iron,	825
Gold,	155	Lead,	1213
Cadmium,	407	Platinum,	1243
Zinc,	414	Mercury,	5550
Tin,	734		

On comparing this list with the list of thermal conductivities, § 449, it will be observed that the order is precisely the same as far as the comparison extends, and that the numerical values are nearly in inverse proportion, showing that electrical and thermal *conductivities* are nearly in direct proportion.

745. Resistance of Liquids.—The resistance of liquids can be determined on similar principles, the current being transmitted between two parallel plates of metal immersed in the liquid. One form of apparatus for this purpose is represented in Fig. 482. Care must be taken to employ metals which will not give rise to electromotive force by chemical action.

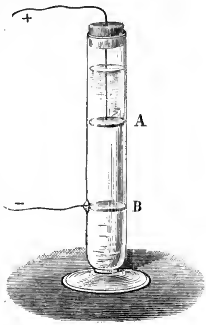


Fig. 482.—Resistance of Liquids.

The resistance even of the best conducting liquids, except mercury, is enormously greater than that of metals. For instance, in round numbers, the resistance of dilute sulphuric acid is a million times, and that of solution of sulphate of copper ten million times greater than that of pure silver. The resistance of pure water is very much greater than either of these.

In the cells of a galvanic battery, the current has to traverse liquid conductors, and the resistance of these is sometimes a large part of the whole resistance in circuit. It is diminished by bringing the plates nearer together, and by increasing their size, since the former change involves diminution of length, and the latter increase of sectional area in the liquid conductor to be traversed. This is the only advantage of large plates over small ones, the electro-motive force being the same for both. The advantage of the double coppers in Wollaston's battery (§ 702) is similarly explained, the resistance with this arrangement being about half what it would be with copper on only one side of the zinc, at the same distance.

746. Choice of Galvanometer.—The circumstances which should influence the choice of a galvanometer coil for a particular purpose, will now be intelligible. If stout wire is employed, the resistance is small, but it is not practicable to multiply convolutions to any great extent. Short coils of thick wire are accordingly employed in connection with thermo-piles, the resistance in the pile itself being so small that the total resistance in circuit is nearly proportional to the number of convolutions.

When, on the other hand, the resistance in the other parts of the circuit is very considerable, the resistance of the galvanometer coil becomes comparatively immaterial, so that, within moderate limits, the deflection of the needle is nearly proportional to the number of

convolutions, and a coil composed of a great length of wire will give the maximum effect.

In both cases, for a given length and diameter of wire, the sensibility increases with the conductivity of the metal composing the wire. Copper is the metal universally employed, and its purity is of immense importance for purposes of delicacy, as impurities often increase its resistance by 50 or even 100 per cent.

747. Divided Circuits.—When two or more wires are connected *in series*, so that whatever flows through one must flow through all, *the resistance of the whole is the sum of the resistances of the wires composing it.*

On the other hand, when two or more wires are arranged *in parallel circuit*, so as to constitute so many independent channels of communication between the same two points, the joint resistance is evidently less than the resistance of any one of the wires. A circuit is said to be *divided* when such an arrangement occurs in any part of it, and the current is also said to be divided. Thus, in Fig. 483 the current from the positive source s to the negative source s' is divided between the two wires *acb*, *adb*, which connect the small mercury cups *a*, *b*.

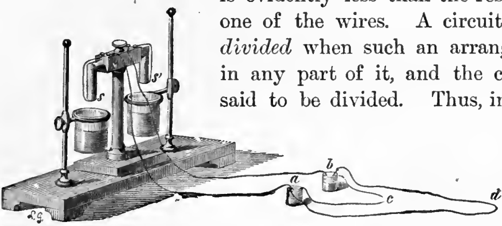


Fig. 483.—Divided Circuit.

Let E denote the difference of potential between the two points which are thus joined, and r_1, r_2, &c., the resistances of the separate paths; then the currents through the separate paths will be $\frac{E}{r_1}$, $\frac{E}{r_2}$, &c. The total current between the two points is the sum of these, or $E\left(\frac{1}{r_1}+\frac{1}{r_2}+\text{&c.}\right)$, and this must be equal to $\frac{E}{R}$, where R denotes the resistance of a single wire equivalent to the system. Hence we have

$$\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2}+\text{&c.};$$

or, *the reciprocal of the joint resistance is the sum of the reciprocals of the separate resistances.*

748. Arrangement of Cells in Battery.—Suppose that we have a

number n of precisely similar cells, each having electro-motive force e and resistance r, and that we connect them in a series, as in Figs. 447, 458, with a conductor of resistance R joining their poles. The whole electro-motive force in the circuit will then be $n\,e$, and the whole resistance will be $n\,r + \mathrm{R}$; hence the strength of current will be

$$\mathrm{C} = \frac{n\,e}{n\,r + \mathrm{R}}$$

This formula shows that, if the external resistance R is much greater than the resistance in the battery $n\,r$, any change in the number of cells will produce a nearly proportional change in the current; but that when the external resistance is much less than that of one cell, as is the case when the poles are connected by a short thick wire, a change in the number of cells affects numerator and denominator almost alike, and produces no sensible change in the current. It is impossible, by connecting any number of similar cells *in a series*, to obtain a current exceeding $\frac{e}{r}$, which is precisely the current which one of the cells would give alone if its plates were well connected by a short thick wire.

It is possible, however, by a different arrangement of the cells, to obtain a current about n times stronger than this, namely, by con-

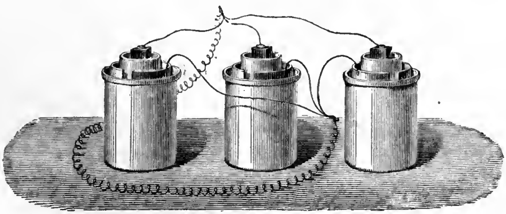


Fig. 484.—Cells with similar Plates connected.

necting all the zinc plates to one end of a conductor, and all the carbons or coppers to the other end, as in Fig. 484. In the arrangement of three cells here figured, the current which passes through the spiral connecting wire is the sum of the currents which the three cells would give separately. The arrangement is equivalent to a single cell with plates three times as large superficially, and at the same

distance apart. The electro-motive force with n cells so arranged is simply e, but the resistance is only $\frac{r}{n}$ + R, so that the current is

$$C = \frac{e}{\frac{r}{n}+R} = \frac{ne}{r+nR}.$$

This system of arrangement may be called *arranging the cells as one element*, or arranging them *in parallel circuit.* It has sometimes been called the *arrangement for quantity*, the arrangement in a series being called the *arrangement for intensity.*

If in Fig. 484 we substitute for each of the three cells a *series* consisting of four cells, the electro-motive force in circuit will be $4e$, and the resistance in circuit will be $\frac{4r}{3}$ + R, for each series has a resistance of $4r$, and three parallel series connected at the ends are equivalent to a single series, of the same electro-motive force as one of the component series, and of one-third the resistance. The current will therefore be

$$C = \frac{4e}{\frac{4r}{3}+R} = \frac{12e}{4r+3R} = \frac{e}{\frac{r}{3}+\frac{R}{4}}.$$

The question often arises, What is the best manner of grouping a given number of cells in order to give the strongest possible current through a given external conductor? The answer is, they should be so grouped that the internal and external resistance should be as nearly as possible equal; for example, if we have 12 cells as above, and the resistance R in the given conductor is $\frac{4}{3}$ of the resistance of one of these cells, the arrangement just described is the best.[1]

749. Distribution of Potential in a Voltaic Circuit.—When the electrodes of a battery are not connected, their difference of potential, supposing them to be of the same metal, is a measure of the electromotive force of the battery. On joining them by a connecting wire, their difference of potential will be diminished, and will be the same

[1] Instead of 3 and 4, put x for the number of series, and y for the number of cells in a series. Then the current will be $\frac{e}{\frac{r}{x}+\frac{R}{y}}$, and will vary inversely as $\frac{r}{x}+\frac{R}{y}$. Now the product of $\frac{r}{x}$ and $\frac{R}{y}$ is given, being the quotient of rR by the whole number of cells; and when the product of two variables is given, their sum is least when they are equal, and increases as they are made more and more unequal. As x and y must be integers, exact equality cannot generally be obtained.

fraction of the whole electro-motive force that the resistance in the connecting wire is of the whole resistance. This follows at once from the principle that the gradual falls of potential in different portions of the same single circuit are directly as their resistances.

In a battery of four cells, like that represented in Fig. 447, when the extreme plates are connected by a wire whose resistance is double that of the battery, the fall of potential in the connecting wire will be two-thirds, and the fall of potential in the battery will be one-third, of the whole electro-motive force. To avoid fractions, let the electro-motive force of each cell be denoted by 3. Then the total electro-motive force will be 12, the fall of potential in the connecting wire will be 8, in the battery 4, and in each cell 1.

The distribution of potential, both before and after making connection, is exhibited in the two columns subjoined, the connecting wire being supposed to be of copper, and to be connected with the earth close to its junction with the first zinc plate, so that this end of the wire will always be at zero potential. We may suppose connection to be broken by disconnecting the other end of the copper wire from the last copper plate.

CONNECTION BROKEN.

		Potentials.
Copper Wire,		0
1st Cell	Zinc plate,	3
	Acid,	3
	Copper plate,	3
2d Cell	Zinc plate,	6
	Acid,	6
	Copper plate,	6
3d Cell	Zinc plate,	9
	Acid,	9
	Copper plate,	9
4th Cell	Zinc plate,	12
	Acid,	12
	Copper plate,	12

CONNECTION MADE.

		Potentials.
Copper Wire,		8 to 0
1st Cell	Zinc plate,	3
	Acid,	3 to 2
	Copper plate,	2
2d Cell	Zinc plate,	5
	Acid,	5 to 4
	Copper plate,	4
3d Cell	Zinc plate,	7
	Acid,	7 to 6
	Copper plate,	6
4th Cell	Zinc plate,	9
	Acid,	9 to 8
	Copper plate,	8

The distribution of potential when connection is made is graphically represented by the crooked line A 3 2 5 4 7 6 9 C (Fig. 485); resistances being represented by horizontal, and potentials by vertical distances. A C represents the total resistance in circuit; A B being the resistance of the battery, and B C that of the connecting wire.

A D represents the total electro-motive force. The points C and A are to be regarded as identical; in other words, the diagram ought to be bent round a cylinder so as to make one of these points fall upon the other.

750. Measurement of Resistance of Battery.—The resistance of a battery may be measured in various ways, of which we shall begin with the simplest.

Let the poles of the battery be directly connected with a galvanometer whose resistance is either very small or accurately known, and

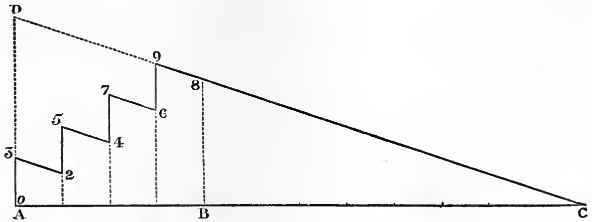


Fig. 485.—Curve of Potential for Closed Circuit.

let the deflection be noted. Then let a wire of known resistance be introduced into the circuit, and the deflection again noted. The two currents thus measured will be inversely as the resistances, since the electro-motive force is the same in both cases. Let the resistance of the galvanometer coil be denoted by G, that of the wire introduced in the second case by W, and that of the battery by x. Then if the amounts of current be denoted by C_1, C_2, we have $\frac{C_1}{C_2} = \frac{x + G + W}{x + G}$; whence x can be determined.

This mode of determination is not very accurate; in the first place, because the electro-motive force of a battery is not a constant quantity but usually diminishes as the current increases; and secondly, because the measurement of a current by a galvanometer is not a very exact operation. Some better methods will be described later.

751. Measurement of Electro-motive Force.—The most direct mode of comparing the electro-motive forces of cells of different kinds, would be to observe how many cells of the one kind arranged in series must be opposed to a given number of the other kind, in order that the resultant electro-motive force may be nil as indicated by the

absence of deflection in a galvanometer forming part of the circuit. For example, if two Daniell's cells and one Grove's cell be connected with each other and with a galvanometer, in such a manner that the current due to the Daniell is in one direction, and that due to the Grove is in the opposite direction, the current actually produced will be in the direction of the greater electro-motive force. It will thus be shown whether the electro-motive force of a Grove's cell is more or less than double that of a Daniell's. This method has not been much used.

Another method of comparison consists in first connecting the two cells to be compared, so that their electro-motive forces tend the same way, and then again connecting them, so that they tend opposite ways, the resultant current being observed in both cases with the same galvanometer. The resistance in circuit is the same in both cases, being the resistance of the galvanometer plus the sum of the resistances of the cells; hence the currents will be simply as the electro-motive forces, that is to say, as E_1+E_2 to E_1-E_2, if E_1 and E_2 denote the electro-motive forces of the cells. Hence the ratio of E_1 to E_2 is easily computed.

This method is liable to the objection that increase of current gives increase of polarization (§ 731) and consequent diminution of electro-motive force; besides the objection that the measurement depends upon the reduction of the indications of a galvanometer to proportional measure.

752. Determination by Electrometer.—The statical electro-motive force of a battery or cell (that is, its electro-motive force when no current is passing, the poles being disconnected) can be directly observed by connecting its poles to opposite quadrants of Thomson's electrometer; for the instrument will then show the difference of potential between them, and this difference of potential is the electro-motive force.

753. Latimer Clark's Method.—Another mode of statically comparing electro-motive forces is illustrated by Fig. 486. A battery of greater electro-motive force than either of those which are to be compared is employed to send a current round a circuit containing a series of known resistances. By Ohm's law, the difference of potential between two points in this circuit is proportional to the resistance between them. In the

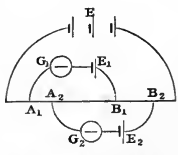


Fig. 486.—Latimer Clark's Method.

method now to be explained we find two points in it whose difference of potential is equal to the statical difference of potential between the poles of one battery; and also two points whose difference of potential is that of the other battery. Then the ratio of the electro-motive forces will be the ratio of the resistances between these points, which are known. E_1 and E_2 in the figure are the two batteries which are to be compared, and E is the third battery, more powerful than either, which, alone of the three, gives a current when the adjustments are complete. G_1 is a galvanometer which shows what current is passing through the battery E_1, and this current is to be reduced to zero by properly choosing the points A_1 B_1. In like manner the current through E_2 and G_2 is to be reduced to zero by proper choice of the points A_2 B_2. Then the electro-motive force of E_1 is to that of E_2 as the resistance A_1 B_1 is to the resistance A_2 B_2.

By this method Mr. Latimer Clark has found that the statical electro-motive forces of a cell of Grove, Bunsen, Daniell, and Wollaston are approximately as 100, 98, 56, and 46. The last of these, being a one-fluid battery, is liable to fall off 50 per cent. or more when in action, owing to the deposition of hydrogen on the copper plate.

754. Simultaneous Determination of Electro-motive Force and Resistance.—The following method gives the electro-motive force of a battery through which a current is passing; and also gives the resistance of the battery.

B (Fig. 487) is the battery, which sends a current through the circuit P S Q R, containing two variable resistances, R and S. The resistance S is to be varied until the difference of potential between its ends P and Q is equal to the statical difference of potential between the poles of a standard cell C, as shown by the absence of a current through the galvanometer G.

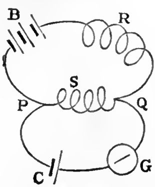


Fig. 487.

R is then to be increased by any convenient amount r, and S is to be increased by an amount s such that the galvanometer again indicates no current.

Then if e denote the statical electro-motive force of the standard cell, and E the electro-motive force of the battery B during the experiment, the strength of the current through S in the first obser-

vation is $\frac{e}{S}$, and is also $\frac{E}{B+S+R}$. We may therefore equate these two expressions, and by alternation we have

$$\frac{E}{e}=\frac{B+S+R}{S}. \tag{1}$$

Similarly, from the second experiment, we have

$$\frac{E}{e}=\frac{B+S+s+R+r}{S+s}. \tag{2}$$

By taking the differences of numerators and denominators we deduce

$$\frac{E}{e}=\frac{s+r}{s}, \tag{3}$$

an equation which determines the value of E, since e, s, and r are known.

Again by equating the right-hand members of (1) and (3) and subtracting unity, we obtain $\frac{B+R}{S}=\frac{r}{s}$, whence $B=\frac{Sr}{s}-R$; thus the resistance B of the battery is determined. It is advantageous to make R zero.

755. Clark's Standard Cell.—The standard cell commonly employed for such comparisons is that of Mr. Latimer Clark. "It is formed by employing pure mercury as the negative element, the mercury being covered by a paste made by boiling mercurous sulphate in a thoroughly saturated solution of zinc sulphate, the positive element consisting of pure distilled zinc resting on the paste." It must not be used for producing a current; but its statical electro-motive force is very constant and permanent.

756. Wheatstone's Bridge.—In any wire through which a current is flowing steadily, without leakage or lateral offshoots, the amount of the current is equal to the *difference of potential between the ends of the wire, divided by the resistance of the wire,* the units employed being the same as those which make $C=\frac{E}{R}$ for the whole circuit. The same thing is true for *any portion* of the length of such a wire, and, still more generally, for *any portion* of a circuit, whether single or divided, *terminated by equipotential cross-sections,* provided that no source of electro-motive force occurs in it. It follows that, in travelling along such a wire with the current, the fall of potential is proportional to the resistance travelled over, or *equal falls of potential occur in traversing equal resistances.* This rule does not apply to the comparison of the two independent channels of a divided cir-

cuit, unless equal currents are passing through them. It applies to the comparison of any two wires which are conveying equal currents, but it is not applicable to the comparison even of different portions of the same wire if, owing to leakage, the current is unequal at different parts of its length.

Equality of potential in two points of a divided circuit can be tested by observing whether, when they are connected by a cross-channel, any current passes between them. This principle was applied, first by Christie, and afterwards by Wheatstone, Thomson, and others, to the measurement of resistances. The apparatus employed for the purpose is known as *Wheatstone's bridge*, and is typically represented in Fig. 488.

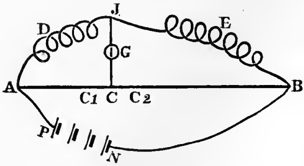


Fig. 488.—Wheatstone's Bridge.

The poles P, N of a battery are connected by two independent channels of communication ACB, ADJEB. The former is a uniform wire; the latter consists of the wire D, whose resistance is to be determined, and of a standard resistance-coil E. The observation has for its immediate object to find what point in the uniform wire AB has the same potential as the junction J of the other two. When this point C is found, and connected with J through a galvanometer G, no current will pass across, and the needle of the galvanometer will not move. If a point C_1 on the positive side of C were connected with J, a current would run from C_1 to J, and if a point C_2 on the negative side were connected, the current would be from J to C_2. The deflection diminishes as the right point C is approached, and becomes reversed in passing it. When it is found we know that the resistances in AC and CB have the same ratio as those of D and E, each of those ratios being in fact equal to the fall of potential between A and JC divided by the fall between JC and B. As the resistance of E is known, and the resistances of AC, CB are as their lengths, which are indicated on a divided scale, the resistance of D can be computed by simple proportion.

In Wheatstone's original arrangement, the resistances of the two portions AC, CB were equal, and the resistances of the other two portions ADJ, JEB were made equal by the help of a rheostat.

757. Loop Test.—The following method of finding the position of a fault in a telegraph wire is an application of the principle of Wheatstone's bridge. We suppose the fault to consist in loss of insulation at some point of the wire, so that the resistance between this point and the ground is much less than it ought to be, though it may still be as great as that of some miles of wire.

The fault is known to be between two given stations. At one of these stations let the end of the faulty wire be joined to the end of another wire; and at the other station let the ends A, B, of the same two wires be put in connection with the two poles of a battery (Fig. 489). Also let A and B be connected by a circuit containing

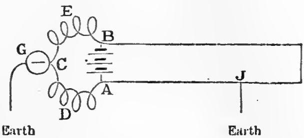


Fig. 489.—Loop Test.

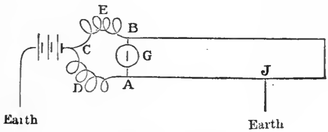


Fig. 490.—Loop Test.

two variable resistances D, E, and let an intermediate point C be connected, through a galvanometer G, with the ground. Let the resistances D, E, be made such that no currrent goes through the galvanometer. Then we know that the point C has the same potential as the earth, and in these circumstances the faulty point J of the wire will also be at the potential of the earth; for if there were a current flowing through the fault to the earth the battery would be steadily giving off electricity of one sign while having no outlet for electricity of the opposite sign, and this cannot be. The points J and C are therefore at the same potential, like the points J and C in Fig. 488; and a comparison of the two figures shows that the same reasoning applies to both. The loop A J B formed by the two telegraph wires is therefore divided by the point J in the ratio of the two known resistances D and E. That is, we have $\frac{\text{resistance of A J}}{\text{resistance of B J}}=\frac{D}{E}$. This determines the position of the point J.

The positions of the battery and galvanometer may be interchanged, as in Fig. 490, and the equation above obtained will still apply; for when no current flows through the galvanometer in this new arrangement, the two paths C D A J and C E B J, which lead from C to J, must be divided proportionally at A and B.

758. Conjugate Branches.—Wheatstone's bridge may be otherwise described as consisting of six branches connecting four points, two and two, in every possible way, the four points being A, B, C, J in Fig. 488. A battery is inserted in the branch which connects any two of these points, A and B, and a galvanometer is inserted in the branch which connects the other two, C and J. These two branches may be called *opposite*, and in like manner A C is opposite to B J, and B C to A J. The condition of no current going through the galvanometer is expressed in § 756 as a proportion. Multiplying extremes and means, and writing the names of the branches for the resistances in them, the condition is

$$AC \,.\, BJ = BC \,.\, AJ,$$

where each member of the equation is the product of the resistances in opposite branches. When this condition is fulfilled, the remaining pair of opposite branches A B and C J are conjugate, that is to say, a battery in one produces no current in the other. The symmetry of the relations shows that the battery may change places with the galvanometer.

759. Conjugate Branches when there are Several Batteries.—When there are batteries in more branches than one, the current in any branch will be the algebraical sum of the currents due to the several batteries considered separately. Hence when there is equality between the two products of opposite resistances, as in last section, the current in either of the two remaining branches will be independent of the electro-motive force of the battery in the other; and these two branches are still said to be conjugate. In estimating the resistance of any branch which contains a battery, the resistance of the battery must of course be included.

Thus far we have not discussed the effect of change of resistance in one of two conjugate branches. The introduction of additional resistance into any branch can affect the current in the rest only by altering the difference of potentials between the ends of this branch; and the same remark applies to the introduction of a source of electro-motive force into any branch. Two changes, one of resistance, and the other of electro-motive force, in a branch, will have the same effect on the rest of the circuit, if they have the same effect on the difference of potentials of the ends of this branch. Hence if the current in one of two branches be independent of the electromotive force in the other, it must also be independent of the resistance in the other.

As this reasoning may appear doubtful to some of our readers, we subjoin a formal investigation leading to the same result.

760. Investigation of Condition of Conjugateness.—Let A, B, C, J (Fig. 488 or Fig. 491), be four points connected, two and two, by six branches. Let the resistance in the branch connecting A and B be denoted by A B or B A, and the electro-motive force in it (positive if tending from A to B) by ab. Let the current in this branch (positive if from A to B) be denoted by γ, and the currents in the branches B C, C A, by α, β. Then the current in the branch A J (positive if from A to J) will be $\beta-\gamma$; for this current together with γ carries off from A the supply brought by β. Similarly, the currents in B J, C J, will be $\gamma-\alpha$, $\alpha-\beta$. Then, since the sum of the falls of potential in travelling round a circuit must equal the sum of the rises, we have, for the circuit J B C, the equation

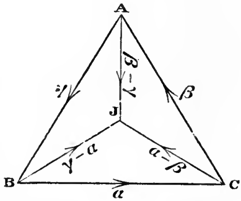


Fig. 491.—Theory of Conjugate Branches.

$$\alpha \,.\, \mathrm{BC} + (\alpha-\beta)\, \mathrm{CJ} + (\alpha-\gamma)\, \mathrm{JB} = bc + cj + jb.$$

Similarly, for the circuits J C A, J A B, we have

$$\beta \,.\, \mathrm{CA} + (\beta-\gamma)\, \mathrm{AJ} + (\beta-\alpha)\, \mathrm{JC} = ca + aj + jc$$
$$\gamma \,.\, \mathrm{AB} + (\gamma-\alpha)\, \mathrm{BJ} + (\gamma-\beta)\, \mathrm{JA} = ab + bj + ja.$$

These three equations are sufficient to determine the three currents α, β, γ, in terms of the electro-motive forces and resistances. Multiplying the equations in order, by $1, l, m$ (l and m being multipliers to be afterwards determined), and adding; the coefficients of α, β, γ, will be

$$\mathrm{BC} + (1-l)\, \mathrm{CJ} + (1-m)\, \mathrm{BJ},$$
$$l \,.\, \mathrm{CA} + (l-m)\, \mathrm{AJ} + (l-1)\, \mathrm{CJ},$$
$$m \,.\, \mathrm{AB} + (m-1)\, \mathrm{BJ} + (m-l)\, \mathrm{AJ},$$

and the second member of the equation will be

$$bc + l \,.\, ca + m \,.\, ab + (l-m)\, aj + (m-1)\, bj + (1-l)\, cj.$$

To find the value of α, we must equate the coefficients of β and γ to zero, and then divide the second member by the coefficient of α. The electro-motive force aj appears only in the term $(l-m)\,aj$, and the resistance AJ only in the terms $(l-m)$ AJ and $(m-l)$ AJ. Hence the equality of l to m is the condition alike of the disappearance of

$a j$ and of A J. Putting $l=m$, and equating the coefficients of β and γ to zero, we have

$$l=\frac{CJ}{CA+CJ}=\frac{BJ}{AB+BJ},$$

whence

$$CJ.AB=BJ.CA,$$

which is, accordingly, the condition of conjugateness. That is to say, *if the product of one pair of opposite resistances be equal to the product of another pair, the remaining pair of branches will be so related that the current in each is independent of the electro-motive force and resistance in the other.*

761. Thomson's Method of Measuring the Resistance of a Galvanometer.—The resistance of a galvanometer can be measured without the use of another galvanometer, by the following method, due to Sir Wm. Thomson.

In a system of six branches joining four points, let a battery and a contact key respectively be in one pair of opposite branches. Then, if the products of the resistances in opposite branches be equal for the four remaining pairs, we know by § 758 that no current will pass through the branch containing the key, and hence making or breaking contact with the key will be nugatory; hence the galvanometer will not have its deflection altered by making or breaking contact with the key. The experiment is to be conducted by altering the resistance in one of the branches until the key has no effect on the galvanometer. The resistance of the galvanometer is then calculated from the equality of the products of opposite pairs.

This method was suggested by the following.

762. Mance's Method of Finding the Resistance of a Battery.—In this method a galvanometer and a contact key are in a pair of opposite branches, and the battery is in one of the four remaining branches, while the other three contain known resistances. The observation is made by varying one of these resistances till the galvanometer is not affected by the key. The branches containing the key and the galvanometer are then conjugate (and the resistance of the battery can be calculated), if the putting down of the key does not alter the electro-motive force of the battery. This condition is seldom fulfilled.

In this method, as well as in that described in the preceding section, the galvanometer does not stand at zero, but shows a steady deflection, which is unaltered by opening or closing the branch containing the key.

CHAPTER LVII.

RELATIONS BETWEEN ELECTRICITY AND HEAT.

763. Heating of Wires.—The heating of a wire by the passage of a current may conveniently be exhibited by the aid of the apparatus represented in Fig. 492. Two uprights mounted on a stand are furnished, at different heights, with pairs of insulated binding-screws $a\,a'$, $b\,b'$, $c\,c'$, having wires stretched between them. A current can thus be sent through any one of the wires, by connecting the terminals of a battery with the binding-screws at its extremities. When this is done with a battery of suitable power, the wire is first seen to droop in consequence of expansion, then to redden, and finally to melt, becoming inflamed if the metal is sufficiently combustible.

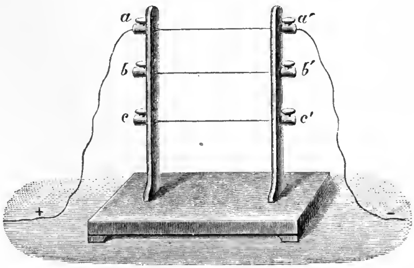


Fig. 492.—Stand for Heating Wires.

If a file is attached to one of the terminals of a battery, and the other terminal is drawn along the file, a rapid succession of sparks will be obtained; and if the battery be sufficiently powerful, globules of incandescent metal will be scattered about with brilliant effect.

764. Joule's Law.—The energy of a current is equal to the product of the quantity of electricity that passes and the electro-motive force that drives it. As the numerical measure of a current is the quantity of electricity which passes in unit time, it follows that the energy of a current C lasting for a time t, is ECt, E denoting the electro-motive

force. But again, by Ohm's law, E is equal to the product of the current C and the whole resistance R. The expression for the energy therefore becomes

$$C^2 R t, \tag{1}$$

and this energy is all transformed into heat in the circuit, subject to a small correction for the Peltier and Thomson effects which will be described in a later section (§ 771). It has accordingly been found, first by Joule, and afterwards by Lenz, Becquerel, and others, that the formula C^2Rt represents the quantity of heat generated by a current under ordinary circumstances. The experiments have usually been conducted by passing a current through a spiral of wire immersed in water or alcohol, and observing the elevation of temperature of the liquid.

This law of Joule's, like that of Ohm, may be applied to any part of a circuit, as well as to the circuit considered as a whole; that is to say, if the circuit consists of parts whose resistances are $r_1, r_2, \ldots,$ the quantities of heat generated in them are respectively $C^2 r_1 t$, $C^2 r_2 t, \ldots,$ and are therefore proportional to the resistances $r_1, r_2 \ldots$ of the respective parts, since C and t are necessarily the same for all.

765. Relation of Heat in Circuit to Chemical Action in Battery.— The energy of a current, and consequently the heat developed in the circuit, is the exact equivalent of the potential energy of chemical affinity which runs down in the cells of the battery. This fact, first verified approximately by Joule, has been more accurately confirmed by the experiments of Favre, who introduced into the muffle of his mercurial calorimeter, already described and figured in § 509, a small voltaic cell with its poles connected by a fine wire. He found that the consumption of 33 grammes of zinc in the cell corresponded to a generation of heat amounting to 18,796 gramme-degrees. But the chemical action in the cell is complex. The 33 grammes of zinc unite with 8 grammes of oxygen, and in so doing generate 42,451 gramme-degrees. The combination of these 41 grammes of oxide of zinc with 40 grammes of sulphuric acid, produces 10,456 gramme-degrees, making in all 52,907. But an equivalent of water undergoes decomposition, and this *absorbs* 34,463, which must be subtracted from the above sum, leaving 18,444 gramme-degrees as the balance of heat generated in the whole complex action. The heat actually observed in the experiment agrees almost precisely with this calculated amount. (Compare § 734.)

766. Distribution of Heat in Circuit.—These experiments also served to verify the application of Joule's law to each part of the circuit considered separately. By introducing the cell into the muffle whilst a spiral of fine wire connecting the poles was outside, and then introducing the spiral while the cell was outside, Favre was able to measure separately the heat generated in the cell and in the spiral, and these were found to be proportional to their resistances.

If wires of different diameter or of different electrical conductivity form parts of the same circuit, so as to be traversed by the same current, the bad conductors will become more heated than the good, and the fine wires more than the coarse. All parts of the length of a uniform wire will be uniformly heated. The specific resistance of platinum is ten times greater than that of copper; hence ten times as much heat will be generated in a platinum as in a copper wire by a given current, if the diameters of the two wires be the same.

The *elevation of temperature* is greater in a fine than in a coarse wire, not only because of its greater resistance, which leads to the development of a greater quantity of heat in it, but also on account of its smaller capacity for heat, and its smaller surface. When the current is passed for so short a time that the heat emitted may be neglected, the elevation of temperature varies directly as the resistance per unit length, and inversely as the capacity per unit length. The resistance varies inversely and the capacity directly as the section of the wire, and hence the elevation of temperature is inversely as the square of the section, or as the fourth power of the diameter.

On the other hand, if the current be continued till the permanent temperature is attained, capacity ceases to have any influence, and the heat emitted in unit time must be equal to the heat received. If x denote the elevation of temperature, the heat emitted is approximately $2\pi r \mathrm{B} x$ by Newton's law (§ 461), r being the radius of the wire, and B a constant. The heat received is $\frac{\mathrm{A}}{\pi r^2}$, A being another constant. By equating these two expressions, we find that $r^3 x$ is equal to a constant, and hence x varies inversely as r^3, that is, the elevation of temperature is inversely as the cube of the diameter.

To obtain the most rapid production of heat in the circuit considered as a whole, we must reduce the resistance to a minimum; for the heat produced in unit time is EC, which, by Ohm's law, is the same as $\frac{\mathrm{E}^2}{\mathrm{R}}$, and therefore varies inversely as R the total resistance.

767. Mechanical Work done by Current.—Favre's experiments also furnished a confirmation of the fact, that when a current is called upon to perform mechanical work, the amount of heat generated in the circuit is diminished by the equivalent of this work. He inclosed a battery of five cells in the muffle of one calorimeter, and an electro-magnet in another calorimeter; the connections between the coil of the electro-magnet and the poles of the battery being made by short thick wires whose resistance could be neglected. The electro-magnet attracted an armature, and thus raised a weight by means of external pulleys.

It was found that when the armature was fixed, so that no mechanical work could be performed, the heat developed was the precise equivalent of the chemical action which took place in the battery; but when the electro-magnet was allowed to raise the weight, the amount of heat indicated by the calorimeters was sensibly less. The difference was measured, and compared with the work done in raising the weight. The comparison indicated 444 kilogrammetres of work for each kilogramme-degree of heat that disappeared, a result which agrees sufficiently well with the established value of Joule's equivalent (425 kilogrammetres).

768. Thermo-electric Currents.—Electric currents can be produced by applying heat or cold to one of the junctions in a circuit composed of two different metals. This was first shown by Seebeck of Berlin in 1821. It may be illustrated by employing a rectangular frame (Fig. 493), having three sides formed of a copper plate, and the fourth of a cylinder of bismuth. It must be placed in the magnetic meridian, with a magnetized needle in its interior. On heating one of the junctions with a spirit-lamp, the needle will be deflected in such a direction as to indicate the existence of a current, which in the copper portion of the circuit, flows from the hot to the cold junction, and in the bismuth portion from the cold to the hot. If cold instead of heat be applied to one junction, the direction of the current will still be from the warmer junction through the copper to the colder junction, and from this through the

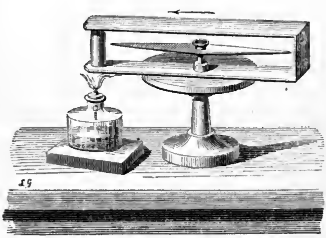


Fig. 493.—Thermo-electric Current.

bismuth to the warmer junction. Antimony, if employed instead of copper, gives a still more powerful effect.

769. Though a circuit composed of bismuth and antimony is specially susceptible of thermo-electric excitation, the property is possessed, in a more or less marked degree, by every circuit composed of two metals, and even by circuits composed of the same metal in different states. If, for example, a knot or a helix (as in Fig. 494), be formed in a piece of platinum wire, and heat applied at one side of it, a current will be indicated by a delicate galvanometer. In metals which are usually heterogeneous in their structure, such as bismuth, it is not uncommon to find currents produced by heating parts which appear quite uniform. If the ends of two copper wires be bent into hooks, and one of them be heated, on placing them in contact, a current will be produced due to the presence of a thin film of oxide on the heated wire. With two platinum wires, no such effect is obtained.

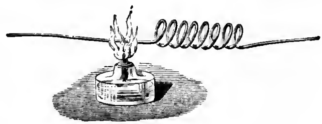


Fig. 494.—Current with one Metal.

770. Thermo-electric Order.—According to Becquerel's experiments, the metals may be ranged in the following order, as regards the direction of the current produced by heating a junction of any two of them:—*Bismuth, platinum, lead, tin, copper, silver, zinc, iron, antimony;* that is to say, if a junction of any two of these metals be heated, the direction of the current at the junction in question will be from that which stands first in the list to the other. His experiments have also established the important fact that the current obtained by heating all the junctions B, C, D, E, F, of a chain of dissimilar metals to one common temperature, is the same as that obtained by uniting the two extreme bars A B, F G, directly to each other, and heating their junction to the same temperature.[1]

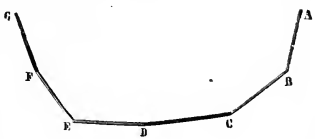


Fig. 495.

[1] The more accurate statement is, that the *electro-motive force* is the same in the two cases. The *current* will be sensibly the same if the resistance in B C D E F is insignificant in comparison with the rest of the circuit. In order that there may be a current, the circuit must of course be completed, and not left open as in Fig. 495. In the case of an open circuit, the result of the heating will simply be to produce difference of potential between

771. Source of Thermo-electric Force.—The source of the electro-motive force in a thermo-electric arrangement is to be found in two effects called, from the names of their discoverers, the Peltier effect and the Thomson effect. They may both be described as *thermal effects of a current which are reversed by reversing the direction of the current.*

Peltier found that if two wires of different metals are joined at one end so as to form a single conductor, the junction becomes hotter when a current is sent through the conductor in one direction than when it is sent in the opposite direction.

Thomson found that a wire of one metal, if it is not at a uniform temperature, but is hotter at one end than at the other, is more heated by a current in one direction than by a current in the opposite direction.

In both cases, the quantity of heat generated in the conductor in unit time by a current C is represented by the expression

$$C^2 R \pm C S,$$

R denoting the resistance of the conductor, S a quantity which we shall suppose to be essentially positive, and the positive or negative sign being taken according to the direction of the current.

The term $\pm$ C S represents an amount of energy which is converted from the electrical to the thermal form by a current in one direction, and from the thermal to the electrical form by a current in the other direction. When the conversion is from the thermal to the electrical form, the current is aided by an electro-motive force S; and when the conversion is from the electrical to the thermal form, the current is opposed by an electro-motive force S. S is the measure of the thermo-electric force, and the direction of this force is always that direction for which the sign of the term C S is negative.

These statements are true both of a thermo-electric circuit as a whole, and of any portion of it considered separately. If the portion considered be an indefinitely short portion containing a junction, the term C^2 R will vanish, and the heating effect will be $\pm$ C S. A junction would therefore be cooled by sending through it a current in the proper direction, if we could prevent the conduction of heat to it from neighbouring parts.

772. Thermo-electric Diagram.—The statement of the quantita-

tive laws of thermo-electricity is greatly facilitated by the use of what is called a thermo-electric diagram.

In a thermo-electric diagram each metal has its own line. Let A A and B B (Fig. 495A) be the lines of two metals, which we will call A and B. Horizontal distances measured from the vertical line $A p q B$ represent absolute temperatures. Let pP and its equal qQ represent any absolute temperature. Then the area of the rectangle Pp qQ represents the thermo-electric force at a junction of the two metals at this temperature. If P be above Q, as in the figure, the force tends from Q to P. The temperature corresponding to the point of intersection N is the *neutral point* of the two metals. At temperatures below N the thermo-electric force at a junction is from the metal B to the metal A, but at temperatures above N it is from A to B, being in both cases directed upwards in the diagram.

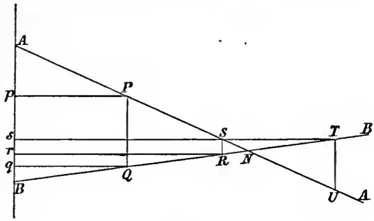


Fig. 495A.

Again if pP and sS represent the temperatures of two points of the metal A, the thermo-electric force in the intervening portion is represented by the area Pp sS, which is bounded on three sides by straight lines, and on the fourth side by the line of the metal, which is not in all cases straight. The direction of this force is from the lower point S to the higher P, so that if the line of the metal slopes like A A in the figure, the force tends from the hot to the cold end. In the portion of the metal B represented by Q R, the force tends from Q to R, that is from the cold to the hot end. In every case the thermo-electric force in each portion of a circuit is directed up-hill in the diagram; and conversely a current generates more heat by running downhill than by running uphill.

773. Thermo-electric Pair.—If the circuit consist simply of a wire of the metal A, joined at both ends to a wire of B, one junction being at the temperature pP or qQ, and the other at the higher temperature sS or rR, both being below the neutral point, the thermo-electric forces in Q R, R S, and S P, all tend in one direction round the circuit, namely, the direction Q R S P Q. Their joint force is represented by the area qQ R S Pp. The force at the

junction P Q is from Q to P, and opposes the other three. It is represented by the area q Q P p, which must accordingly be subtracted. The remainder is the area P Q R S, which accordingly represents the resultant thermo-electric force of the circuit.

774. Properties of the Neutral Point.—Supposing the lower of the two temperatures to be fixed, and to be below the neutral point N, the area P Q R S will be a maximum when S and R coincide with N, being then identical with the triangle P Q N. If the higher

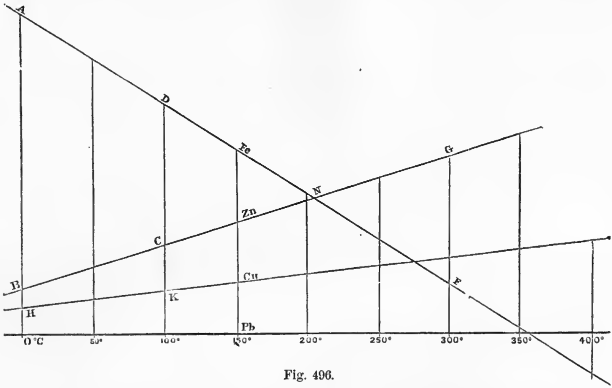


Fig. 496.

temperature be above the neutral point, and be represented by sT, the area which represents the thermo-electric force will be the difference of the two triangles P Q N and N T U. If the lines of the two metals are straight, these two triangles will be equal when one junction is as much above the neutral point as the other is below it, and the thermo-electric force will then be *nil*. At higher temperatures of the hot junction the triangle N T U is larger than the triangle P Q N, and the thermo-electric force is accordingly reversed.

775. General Formula.—Denoting absolute temperature by x, and heights above any fixed horizontal line by y, the thermo-electric force in any part of the circuit is represented by the sum of the elementary strips $x\,d\,y$ taken along the corresponding portion of the diagram, and the resultant thermo-electric force round a circuit is the sum of these strips taken round the whole boundary which represents the circuit. This sum $\Sigma\,x\,d\,y$ is the area enclosed by the boundary, and is positive when the boundary is traced in the

opposite direction to watch hands. The direction of the resultant force will be that which makes this area positive. If one part of the boundary crosses another, we must mark arrows along the boundary in directions corresponding to one direction round the circuit; then areas encircled by arrows against watch hands are to be reckoned positive, and those encircled by arrows with watch hands negative.

776. Application to several Metals.—Fig. 496 is a thermo-electric diagram containing portions of the lines of four metals: Iron (Fe), Zinc (Zn), Copper (Cu), and Lead (Pb).

The Thomson effect is nil in lead, and the lead line is accordingly horizontal. The lines for zinc and copper slope in the direction of ordinary writing; in these the Thomson effect is said to be positive. The line for iron slopes the contrary way, and the Thomson effect in this metal is said to be negative. In a metal for which the Thomson effect is positive, the thermo-electric force due to inequality of temperature tends from the cold to the hot portions of the metal, and conversely the metal would be more heated by a current from hot to cold, than by a current from cold to hot. In a metal in which the Thomson effect is negative the thermo-electric force is from hot to cold, and more heat would be produced by a current from cold to hot than by one from hot to cold.

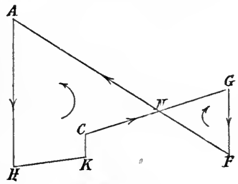


Fig. 496A.

The line of lead, being horizontal, is usually employed as the axis of x, and temperatures are laid off along it. In the figure the area A B C D represents the thermo-electric force of an iron-zinc couple, A H K D that of an iron-copper couple, B H K C that of a zinc-copper couple, and so on, the junctions in each case being at 0° and 100° C.

For a circuit composed of three wires of iron, zinc, and copper respectively, with junctions at the following temperatures:

Iron-zinc 300°, **Zinc-copper 100°;** **Copper-iron 0°,**

we must trace the boundary A H K C G F A, marking our course with arrows, as shown in Fig. 496A. We shall thus obtain the area A H K C N encircled by arrows against watch hands, and the area N G F encircled by arrows with watch hands. The resultant

thermo-electric force is represented by their difference, and is in the direction A H K C G F A.

Numerous experiments, of which the most important are those of Professor Tait, have shown that the lines of most metals are straight within the limits of temperature to which the experiments extended. The line of iron is straight up to a temperature just below redness, but exhibits some remarkable bends before a white heat is reached.

For a further discussion of the laws of thermo-electricity, see the Note at the end of this chapter.

776A. Nomenclature.—It is convenient to call the ordinates in the diagram "*thermo-electric height.*" Thus A B is the difference of the heights of iron and zinc at 0°, or more definitely, it is the height of iron above zinc at 0°.

The difference of the ordinates at two points of one of the lines, divided by the difference of the abscissas, may be called the "*tangent of the slope.*" Its sign is the same as that of the Thomson effect.

The student is likely in the course of his reading to meet with the phrases "electric convection of heat" and "specific heat of electricity." We will therefore explain these somewhat misleading terms.

In a uniform linear conductor along which a current is flowing, there is, in addition to the frictional heating, which is proportional to the square of the current, a warming or cooling effect proportional (at given temperature) to the steepness of the thermometric gradient at the point which is warmed or cooled, changing sign with the gradient, and vanishing at points of maximum or minimum temperature, where the gradient vanishes. This is the Thomson effect. Let us compare it with what happens when a stream of liquid flows through a pipe surrounded at alternate points in its length with hot and cold jackets, the average temperature of the liquid being the same as the average temperature of the pipe. It will carry heat from the hotter to the colder portions, thus cooling the hottest parts, warming the coldest parts, and at the same time carrying forward the points of maximum and minimum temperature. If, at each point of the pipe (supposed straight and horizontal), we erect an ordinate to represent its temperature, and call the curve of which they are the ordinates "the temperature curve;" the effect of the flow of liquid on this curve will be twofold: (1) It will carry the

temperature curve forward; (2) It will make the temperature curve flatter.

In the Thomson effect, an electric current carries the temperature curve forward in copper, and backward in iron; but in neither case does it make the temperature curve flatter. Erroneous statements on this point[1] will be found in some text-books. They have arisen from taking the phrase "electric convection" too literally. In speaking of electric convection, it is customary to say that the "specific heat of electricity" is positive in a metal in which the temperature curve is carried forward, and is negative in a metal in which the temperature curve is carried backward.

777. Thermo-electric Pile.—If a thermo-electric chain be composed

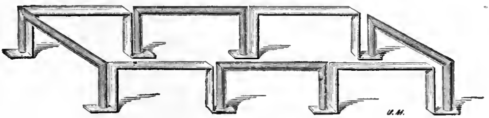


Fig. 497.—Pouillet's Thermo-pile.

of two metals occurring alternately (as in Fig. 497), no effect will be obtained by equally heating *two consecutive* junctions; for the current which would be generated by heating the one is in the opposite direction to that due to the heating of the other. If we number the junctions in order, we shall obtain a current in one direction by heating any junction which bears an odd number, and in the opposite direction by heating any one that bears an even number. The thermo-electric pile, or *thermo-pile*, whose use has been already described in connection with experiments on radiant heat (§ 472), is an arrangement of this kind, in which all the odd junctions are presented together at one end, and all the even junctions at the other, the two metals composing the pile being antimony and bismuth. The electromotive force obtained with a given difference of temperature between the ends of the pile is proportional to the number of junctions, except in so far as accidental differences may exist between different junctions.

Of late years some thermo-piles have been constructed which have sufficient electro-motive force for the deposition of metals from solutions, and they have to some extent been employed commer-

[1] See a discussion in *Nature*, vol. 34, pp. 75, 120, 143.

cially for this purpose. The number of pairs of metals is usually about 70, the materials being in one instance iron and type-metal, in another iron and galæna. These piles have the form of a hollow cylinder with junctions facing alternately inwards and outwards. The inner junctions are exposed to the flame of a Bunsen gas-burner, while the outer junctions are kept cool by the contact of the air.

778. Observations of Temperature by Thermo-electric Junctions.—Thermo-electric currents may be employed either for comparing small differences of temperature (which is the function of the thermo-pile), or for testing equality of temperature. As an example of the latter application, suppose a circuit to be formed of two long wires, one of iron and the other of copper, connected at both ends, and covered with gutta-percha or some other insulator except at the two junctions. Let one junction be lowered to the bottom of a boring, or any other inaccessible place whose temperature we wish to ascertain, and let the other junction be immersed in a vessel of water containing a thermometer. If one of the wires be carried round a galvanometer, the direction in which the needle is deflected will indicate whether the upper or lower junction is the warmer, and if we alter the temperature of the water in the vessel till the deflection is reduced to zero, we know that the two junctions are at the same temperature, which we can read off by the thermometer immersed in the water.

779. Pyro-electricity.—Another relation between heat and electricity may here be mentioned, though it belongs rather to electrostatics than to current electricity.

When a crystal of tourmaline is heated or cooled, observation shows that, while the crystal is gaining heat, one end of it has a charge of positive and the other of negative electricity; and while it is losing heat these charges are reversed. This phenomenon is called pyro-electricity, and it is always associated with a departure from symmetry in crystalline form, which enables us to distinguish one end of the crystal from the other.

780. Effect of Light on Electrical Resistance.—Mr. Willoughby Smith has discovered that the electrical resistance of crystalline selenium is diminished by the action of light. A strong instantaneous effect is observed at the moment when light first falls upon the substance, and the effect gradually increases for some time if the exposure to light is continued. Professor W. G. Adams found that exposure to the light of an ordinary wax taper at a distance

of 20 centims. diminished the resistance of a plate of selenium by about one-eighth part of the whole.

Selenium is a very bad conductor, its resistance being more than a thousand million times that of iron.

The most striking effects are obtained by constructing a so-called "selenium cell" on the following plan. A strip of mica or some other substance of high insulating power is notched at both edges, and a copper wire is wound round it leaving alternate notches vacant. Its ends are secured, one of them being attached to a binding-screw. A second wire is then wound in the intervening notches and similarly secured. It must not touch the first, but must be everywhere very near it. The face of the plate is then thinly covered with selenium, which must be melted on and allowed to cool slowly so as to assume the crystalline form. The selenium affords the only medium of electrical communication between the two wires, and if the two binding-screws are connected with a battery, a high-resistance mirror-galvanometer being also introduced into the circuit, the exposure of the face of the cell to various degrees of light will give strongly marked effects on the galvanometer. If a disc of cardboard be cut away in sectors and rapidly rotated between the face of the cell and the sun or any strong light, in such a manner that the cell is alternately in light and shadow as the sectors pass, the fluctuations of current thus produced can be detected by means of a telephone, which gives a very audible hum. This is a severe test of the quickness of the action, for a thermo-pile gives no sound under the same circumstances. This combination of a selenium cell with a telephone is called a *photophone,* and with a modified form of it articulate sounds have been transmitted to a distance by light. The invention is due to Professor Graham Bell, the inventor of the telephone, and the form of cell above described was introduced by Mr. Shelford Bidwell.

NOTE.

Mathematical Investigation relating to Thermo-electricity.

[The abbreviation *e.m.f.* denotes electro-motive force.]

Let $\pi_1(ab)$ denote the *e.m.f.* tending from the metal A to the metal B at their junction at temperature t_1. It will follow from this definition that $\pi_1(ba) = -\pi_1(ab)$. The experimental fact that, in a closed circuit of three metals

A, B, C at uniform temperature, there is no resultant thermo-electric force, proves that

$$\pi_1(a\,b)+\pi_1(b\,c)+\pi_1(c\,a)=0, \quad \text{or} \quad \pi_1(a\,c)=\pi_1(a\,b)+\pi_1(b\,c). \tag{1}$$

Again, the experimental fact that the resultant *e.m.f.* of a closed circuit is independent of the temperatures of all parts except the junctions, shows that the resultant *e.m.f.* due to difference of temperature in a single metal depends on the temperatures of its ends only, and is independent of its length. The same conclusion might be drawn from the fact that no current is produced in a closed circuit of one homogeneous metal by any distribution of temperature in its various portions. Hence the *e.m.f.* in a short portion of nearly uniform temperature varying from t at one end to $t+d\,t$ at the other, may be expressed as $\sigma\,d\,t$, where σ is a function of t having different values for different metals. The coefficient σ (called the Thomson coefficient) is regarded as positive when the *e.m.f.* tends from the colder to the warmer end. We shall denote its value in the metal A by σ_a, its value in B by σ_b, and so on.

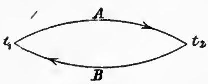


Fig. 497A.

Consider a closed circuit (Fig. 497A), consisting of a wire of one metal A joined at both ends to a wire of another metal B, one junction being at the temperature t_1, and the other at t_2. The resultant *e.m.f.*, regarded as positive when it is in the direction of the arrows, is

$$\pi_1(b\,a)+\int_{t_1}^{t_2}\sigma_a\,d\,t+\pi_2(a\,b)+\int_{t_2}^{t_1}\sigma_b\,d\,t, \tag{2}$$

or

$$\pi_2(a\,b)-\pi_1(a\,b)+\int_{t_1}^{t_2}(\sigma_a-\sigma_b)\,d\,t. \tag{3}$$

In any reversible thermo-dynamic engine, if we divide each portion of heat taken in or given out by the absolute temperature at which the exchange occurs, and reckon heat given out opposite in sign to heat taken in, the sum of the quotients is zero. Applying this principle to the present case, we have

$$\frac{\pi_2(a\,b)}{t_2}-\frac{\pi_1(a\,b)}{t_1}+\int_{t_1}^{t_2}\frac{(\sigma_a-\sigma_b)}{t}\,d\,t=0,$$

or, writing y as an abbreviation for $\dfrac{\pi(a\,b)}{t}$,

$$y_2-y_1+\int_{t_1}^{t_2}\frac{\sigma_a-\sigma_b}{t}\,d\,t=0, \tag{4}$$

By supposing a small change in t_2, while t_1 remains constant, we deduce from (4)

$$\frac{d\,y}{d\,t}+\frac{\sigma_a-\sigma_b}{t}=0, \tag{5}$$

which gives by integration

$$\int_{t_1}^{t_2}(\sigma_a-\sigma_b)\,d\,t=-\int_{y_1}^{y_2}t\,d\,y=t_1y_1-t_2y_2+\int_{t_1}^{t_2}y\,d\,t.$$

But t_1y_1 is $\pi_1(a\,b)$ and t_2y_2 is $\pi_2(a\,b)$. Hence expression (3) for the resultant thermo-electric force in the circuit reduces to

$$\int_{t_1}^{t_2}y\,d\,t, \tag{C}$$

which denotes an area such as A B C D or B H K C in Fig. 496, if y denote the length intercepted between the lines of the two metals on the ordinate corresponding to the abscissa t.

Writing $y\,(a\,b)$ instead of y for greater explicitness, we have, by dividing equation (1) by t_1,

$$y\,(a\,b)+y\,(b\,c)=y\,(a\,c), \tag{7}$$

a property which enables us to combine the lines of more than two metals in the same diagram.

The quantity y in the above investigation is the difference of the ordinates of the two metals A and B in a thermo-electric diagram. The line of some one standard metal is arbitrary both in form and position, and its choice will determine the rest. Adopting as the standard a metal (lead) for which σ is zero at all temperatures, and assigning to it a line which is straight and horizontal, we find from (5), by identifying the standard with A, that for any other metal (identified with B)

$$\frac{\sigma}{t}=\frac{d\,y}{d\,t}. \tag{8}$$

Hence the line of a metal slopes one way or the other according to the sign of σ. The *e.m.f.* due to difference of temperature in a small portion of one metal is $\sigma\,d\,t$, which by (8) is equal to $t\,dy$. It always tends in the direction in which y increases.

The *e.m.f.* at a junction with the standard metal, reckoned positive when it tends from the standard to the other metal, is $t\,y$, and is represented by the area of the rectangle whose sides are the two co-ordinates.

If y_a and y_b are the ordinates of the lines of two metals A and B, y_b-y_a will be the quantity denoted by y in (4), (5), and (6), and by $y\,(a\,b)$ in (7).

If we travel completely round any thermo-electric circuit consisting of any number of metals, and trace the corresponding course on the thermo-electric diagram, this latter course will consist partly of vertical movements corresponding to the junctions, and partly of slanting or horizontal movements along the lines of the metals. In each of these two kinds of movement the *e.m.f.* (reckoned positive if it tends in the direction in which we are travelling) is the sum of the elementary areas $t\,d\,y$. The resultant *e.m.f.* is therefore $\Sigma\,t\,d\,y$ taken all round the course, and this is identical with the area which the course encloses.

"The specific heat of electricity" is a name which has been given to the Thomson coefficient σ for the reason explained in §776A, but it is not desirable that it should be retained, the analogy to convection of heat being very imperfect and misleading. The other coefficient π (more commonly printed Π) is called the Peltier coefficient.

CHAPTER LVIII.

ELECTRO-DYNAMICS.

781. **Meaning of Electro-dynamics.**—A wire through which a current is passing, is found to be capable of producing movements in other wires also conveying currents. The theory of these movements, or more generally, of *the mechanical actions of currents upon one another*, constitutes a distinct branch of electrical science, and is called *electro-dynamics*. It stands in very close relation to electro-magnetism; and if the laws of either of the two sciences are given, those of the other may be deduced as consequences.

The science of electro-dynamics was founded by Ampère. Figs. 498, 499 represent an arrangement which he devised for rendering a conductor movable without interruption of the current conveyed by it.

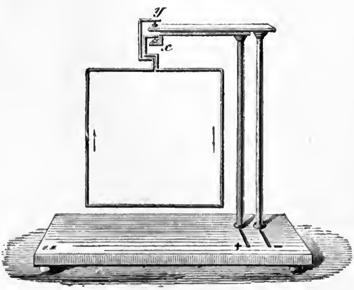


Fig. 498.—Ampère's Stand.

A wire is bent into the form of a nearly complete rectangle, and its two ends terminate in points, one above the other, so arranged that a vertical through the centre of gravity passes through them both. Accordingly, if either or both of these points be supported, the wire can turn freely about this vertical as axis. The points dip into two small metallic cups x y containing mercury, and the weight is usually borne by the upper point alone, which touches the bottom of its cup. The cups are attached to two horizontal arms of metal, supported on metallic pillars, which can be con-

nected with the two terminals of a battery. The wire thus forms part of the circuit, the current being down one side of the rectangle and up the other. Instead of the rectangular the circular form may be employed, as in Fig. 500.

If a magnet be placed beneath, as in Fig. 499, the wire frame will set its plane perpendicular to the length of the magnet, the relative position assumed being the same as if the wire frame were fixed, and the magnet freely suspended, if we neglect the disturbing effect of the earth's magnetism.

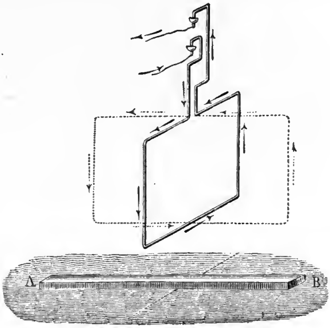


Fig. 499.—Action of Magnet on Movable Circuit.

782. Mutual Forces between Conductors conveying Currents.—The following elementary laws, regarding the mutual forces exerted between conductors through which currents are passing, were established by Ampère. For brevity of expression, it is usual to speak, in this sense, of the *mutual forces between currents*, or of the *mutual mechanical action of currents.*

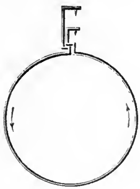


Fig. 500.

I. *Successive portions of the same rectilinear current repel one another.*[1]

This is proved by the aid of two troughs of mercury separated by a partition (Fig. 501). A varnished wire is bent into such a form that two portions of it can float on the surface of the mercury in the two troughs, while connected with each other by an arc passing over the partition. The only portions without varnish are the ends. When the terminals of a battery are inserted in the mercury, opposite the ends, as shown in the figure, the circuit is completed through the wire, and repulsion is exhibited, the wire moving away to the further end of the vessel.

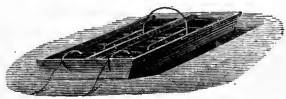


Fig. 501.—Repulsion of Successive Portions.

[1] This first law is not universally accepted, and can scarcely be regarded as resting on the same sure foundation as the rest.

II. *Parallel currents, if in the same direction, attract, and if in the opposite direction, repel each other.*

The apparatus employed for demonstrating this twofold proposition, consists of two metallic pillars *t*, *v* (Fig. 502), which are respectively connected at their upper ends with the two cups of mercury *x*,*y*. The rectangular conductor *a b c d e* is suspended with its terminal points in these cups so as to complete the circuit between the pillars. When the current is passed, this movable conductor always places

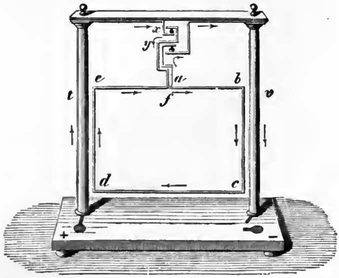


Fig. 502.—Attraction of Parallel Currents.

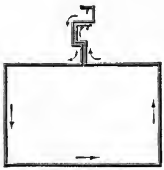


Fig. 503.—Apparatus for Repulsion.

itself so that its plane coincides with that of the two pillars, and so that currents in the same direction in the pillars and in the wire are next each other, as shown in the figure.

For establishing repulsion, a slightly different form of wire is employed, which is represented in Fig. 503. When this is hung from the cups, in the position which the figure indicates, the currents in the pillars are in opposite directions to those in the neighbouring portions of the movable conductor, and the latter accordingly turns away until it is stopped by the collision of the wires above.

III. *Currents whose directions are inclined to each other at any angle, attract each other if they both flow towards the vertex of the angle,*[1] *or if they both flow from it, and repel each other if one of them flows towards the angle, and the other from it.*

A consequence of this law is that two currents, as A B, D C (Fig. 504), crossing one another near O in different planes, tend to set themselves parallel, and so that their directions shall be the same.

[1] If the currents are not in the same plane, we must substitute *the feet of their common perpendicular* for *the vertex of the angle*, in the enunciation of this law.

For there is attraction between the portions A O and D O, and also between the portions O B and O C; whereas there is repulsion between A O and O C, and between O B and O D. Accordingly, if the movable conductor of Fig. 502 or 503 be traversed by a current, and another wire carrying a current be placed horizontally at any angle underneath its lower side, the movable conductor will turn on its point of suspension till it becomes parallel to the wire below it; and in the position of stable equilibrium the current in its lower side will have the same direction as that in the influencing wire.

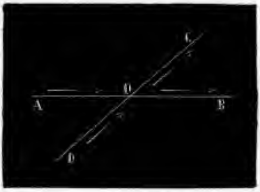


Fig. 504.—Tendency to set Parallel.

783. Continuous Rotation produced by a Circular Current.—Suppose we have a current flowing round a circle (Fig. 505), and also a current flowing along O A, which is approximately a radius of this circle. First let the current in O A be from the centre towards the circumference, as indicated in the figure. Then, by law III., O A is attracted on one side and repelled on the other, both forces combining to make O A sweep round the circle in the opposite direction to that in which the circular current is flowing. If the current in O A were from circumference to centre, the tendency would be for O A to sweep round the circle in the same direction as the circular current.

Fig. 505.—Continuous Rotation of Radial Current.

The reasoning still holds if O A is in a plane parallel to that of the circular current, O being a point on the axis of the circle and the length of O A being not greater than the radius.

A circular current may also produce continuous rotation in a conductor parallel to the axis of the circle, and movable round that axis. Fig. 506 represents an arrangement for obtaining this effect.

A coil of wire through which a current can be sent, is wound round the copper basin E F, its extremities being connected with the binding-screws *m*, *o*. From the centre of the basin rises the little metallic pillar A, terminating above in a cup containing mercury. This pillar is connected with the binding-screw *n*. The basin, which is connected with the binding-screw *p*, contains water mixed with a

little acid to improve its conducting power, and a movable conductor B C rests, by a point, on the bottom of the cup of mercury, while its lowest portion, which consists of a light hoop, dips in the acidulated water. By connecting m and n a single circuit is obtained, of which

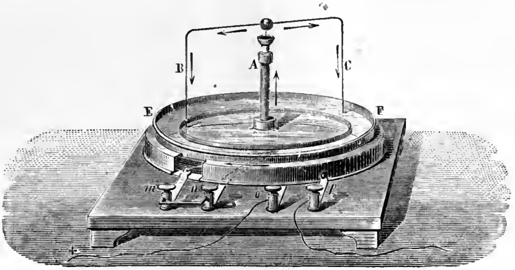


Fig. 506.—Apparatus for Continuous Rotation.

o and p are the terminals, so that if o is connected with the positive and p with the negative pole of a battery, the current entering at o first traverses the wire coil, then ascends the pillar A, returns down the sides B, C to the floating ring and liquid, and so escapes to p. As soon as these connections have been completed, the movable conductor commences continuous rotation in the direction opposite to that of the current in the coil.

If, instead of connecting m and n, we connect n and o, and lead the positive wire from the battery to p and the negative wire to o, the course of the current will be from p to the acid, thence up the sides B, C, and inwards along the top of the movable conductor to the mercury cup, then down the pillar to n, thence to o, and through the coil from o to m in the same direction as in the former experiment; but the rotation of the movable conductor will now occur in the opposite direction to that before observed, and therefore in the same direction as the current.

784. Action of an Indefinite[1] Rectilinear Current upon a Finite Current movable around one Extremity.—A finite current movable about one extremity may also be caused to rotate continuously about this extremity by the action of an indefinite rectilinear current. This is clearly indicated by Fig. 507. In the right-hand diagram, the cur-

[1] The word *indefinite*, in this application, simply means *of great length in comparison with the distance and length of the movable current.*

rent O A flowing outwards from the centre of motion O, and acted on by the indefinite current M N, is first attracted into the position O A′. In this new position it is repelled by n N, and attracted by M n. It is thus brought successively into the positions O A″, OA‴, O A$^{\text{IV}}$. In this last-mentioned position, the two currents being parallel and opposite, there is repulsion; and after passing it, there is again repulsion on one side and attraction on the other, till it is carried round to its first position O A. It is thus kept in continual rotation. If the movable current flows inwards to the centre of motion O, as in the left-hand diagram, while the direction of the indefinite current is the same as before, the direction of rotation will be reversed.

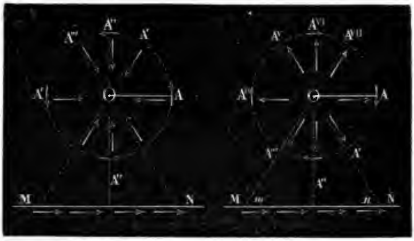


Fig. 507.—Rotation of Radial Current.

785. Action of an Indefinite Rectilinear Current on a Finite Current Perpendicular to it.—Let M N, in the upper half of Fig. 508, be an indefinite rectilinear current, and A D a portion of another current either in the same or in any other plane. In the latter case let D C be the common perpendicular. Then, if the currents have the directions represented by the arrows, an element at p will attract an element at m with a force which we may represent by a line mf'; and an element at p' equal to that at p and situated at the same distance from C on the other side, will repel the element at m with an equal force, represented by mf. Constructing the parallelogram of forces, the resultant force of these two elements upon m is represented by the diagonal m F, which is parallel to M N and in the opposite direction to the indefinite current. As this reasoning applies

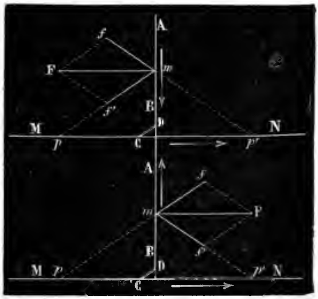


Fig. 508.—Translation Parallel to Indefinite Current.

to all the elements of both currents, it follows that the current A B will experience a force tending to give it a motion of translation parallel to MN. This motion will be opposite to the direction of the indefinite current when the direction of the finite current is towards the common perpendicular D C, as in the upper diagram, and will be in the same direction as the indefinite current when the direction of the finite current is from the common perpendicular, as in the lower diagram.

786. Action upon a Rectangular Current movable about an Axis Perpendicular to an Indefinite Current.—It follows from the preceding section that if a finite current AB (Fig. 509), perpendicular to an

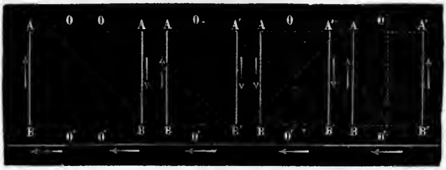


Fig. 509.—Position assumed by Perpendicular Current.

indefinite current, is movable round an axis O O′ parallel to itself, the plane A B O O′ will place itself parallel to the indefinite current, and AB will place itself in advance or in rear of the axis according as the current in A B is from or towards the indefinite current.

If a pair of parallel and opposite currents B A, A′B′, rigidly connected together, and movable round the axis O O′ lying between them, are submitted to the action of the indefinite current, the forces upon them will conspire to place the system in the position indicated in the figure. If the two currents A B, A′B′ are both in the same direction, their tendencies to revolve round the axis O O′ will counteract each other.

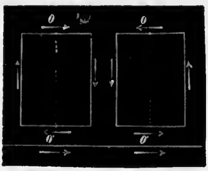


Fig. 510.—Position assumed by Rectangular Current.

The action upon the near side of the rectangle (Fig. 510) contributes to produce the same effect, since this side tends to set itself parallel to the influencing current, and so that the directions of the two shall be the same.

The action upon the further side of the rectangle tends to produce an opposite effect; but, in consequence of the greater distance, this

action is feebler than that upon the near side. The system accordingly tends to take the position of stable equilibrium represented in the right-hand half of the figure. The diagram on the left hand represents a position of unstable equilibrium.

What is here proved for a rectangular current, is true for any closed plane circuit movable round an axis of symmetry perpendicular to an indefinite rectilinear current; that is to say, any such circuit tends to place itself so that the current in the near side of it is in the same direction as the indefinite current.

These results can be verified experimentally by the aid of the apparatus represented in Fig. 511. CC, DD are two cups (shown in section) surrounding the metallic pillar AB at its upper and lower ends, and containing a conducting liquid. The lower cup is insulated from the pillar, and connected with the binding-screw *g*. The liquid in the upper cup CC is connected with the upper end of the pillar by the bent arm *dm*. *o*K is a light horizontal rod supported on a point at B, and carrying a counterpoise K at one end, while the other carries a wire *mnop*, whose two ends *nm* and *op* descend vertically into the two cups, the middle portion of the wire being wrapped tightly round the rod. The binding-screw *f* is connected with the lower end of the pillar. If a current enters at *f* and leaves at *g*, its direction in the long vertical wire *op* will be descending; and it will be ascending, if the connections are reversed. By sending a current at the same time through a long horizontal wire in the neighbourhood of the system, movements will be obtained in accordance with the foregoing conclusions.

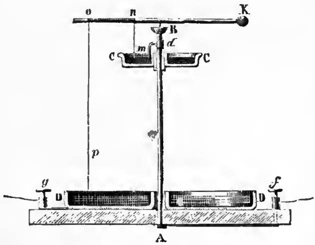


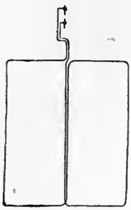
Fig. 511.—Position assumed by Vertical Current.

787. Sinuous Currents.—A sinuous current exhibits the same action as a rectilinear current, provided that they nowhere deviate far from each other. This principle can be exemplified by bringing near to a movable conductor (Fig. 512) another conductor consisting of a wire doubled back upon itself, having one of its portions straight, and the other sinuous, but very near the first. A current sent through this double wire traverses the straight and the sinuous portions in oppo-

site directions, and it will be found that their joint effect upon the movable conductor is inappreciable.

This principle holds not only for rectilinear currents but for currents of any form, and is very extensively employed in the analytical investigations of electro-dynamics. In computing the action exercised by or upon a conductor of any form, it is generally convenient to substitute for the conductor itself an imaginary conductor, nearly coincident with it, and consisting of a succession of short straight portions at right angles to one another (Fig. 513).

788. Mutual Action of Two Elements of Currents.—Ampère based his analytical investigations on the assumption that the action exercised by an element (*i.e.* a very short portion) of one current upon an element of another, consists of a single force directed along the joining line. This assumption conducted him to a formula for the amount



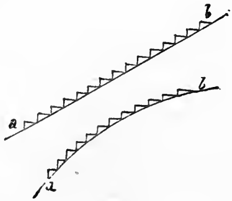


Fig. 512. Sinuous Currents. Fig. 513.

of this force, which has been found to give true results in every case capable of being tested by experiment. Nevertheless, it is by no means certain that either Ampère's formula or his fundamental assumption is true. Other assumptions have been made, leading to other formulæ in contradiction to that of Ampère, which also give true results in every case capable of being experimentally tested. The fact is that experiments can only be performed with complete circuits, and the contradictions which subsist between the different assumptions, in the case of the several parts of a circuit, vanish when the circuit is considered as a whole. All the formulæ, however, agree in making the mutual force or forces between two elements vary inversely as the square of their distance, and directly as the products

of the currents which pass through them. Professor Clerk Maxwell[1] discards all assumptions as to mutual actions between elements at a distance, and employs the principle that a circuit conveying a current always tends to move in such a manner as to increase the number of magnetic force-tubes (in the sense of § 608) which pass through it. The work done in any displacement is measured by the number of tubes thus added; but tubes which cross the circuit in the opposite direction to those due to the current in the circuit are to be regarded as negative.

We have seen (§ 711, 712) that the lines of magnetic force due to a current are circles surrounding it; and also that, when a line of magnetic force cuts a current, the latter experiences a force tending to move it at right angles to the plane of itself and the line of force. In the case of two parallel currents, each is cut at right angles by the lines of magnetic force due to the other; the direction of the force experienced by either current is therefore directly to or from the other current; and the criterion of § 712 will be found to indicate attraction when the directions of the currents are the same, and repulsion when they are opposite.

In Fig. 505 the lines of magnetic force cut OA in a direction perpendicular to the plane of the diagram, OA accordingly experiences a force perpendicular to its own length in the plane of the diagram; and the same remarks apply to AB in Fig. 509. All the experimental facts above detailed are in fact thus explicable. In the experiment of Fig. 501, where the application is scarcely so obvious as in the other cases, the observed motion may be deduced from the direction in which the bridge or arc connecting the two side-wires is cut by the lines of force.[2]

789. Action of the Earth on Currents.—In virtue of terrestrial magnetism, movable circuits, when left to themselves, take up definite positions having well-marked relations to the lines of terrestrial magnetic force. For example, in the apparatus of Fig. 511, the vertical wire *o p* will place itself to the west or east (magnetic) of the pillar AB, according as the current in *op* is ascending or descending. This effect is due to the horizontal component of terrestrial magnetism.

In the apparatus of Fig. 506, if the current be sent only through

[1] Maxwell "On Faraday's Lines of Force." *Camb. Trans.* 1858, p. 50.

[2] Some further remarks on the forces experienced by currents in magnetic fields will be found in Chap. lix.

the movable portion, continuous rotation will be produced, which will be with or against the hands of a watch according as the current in the top wires is inwards or outwards. This effect is due to the vertical component of the earth's magnetism, acting on the currents in the horizontal wires. Vertical lines of magnetic force falling on a horizontal current give the latter a tendency to move perpendicular to its own length in a horizontal plane.

790. Solenoids.—If we suspend from Ampère's stand (Fig. 498) a plane circuit, whether rectangular or circular, it will place itself perpendicular to the magnetic meridian, in such a manner that the current in its lower side is from east to west; or, in other words, so that the ascending current is in its western and the descending current in its eastern side; this effect being due to the action of the horizontal component of terrestrial magnetism upon the ascending and descending parts of the current. If, then, we have a number of such circuits, rigidly connected together at right angles to a common axis, and with their currents all circulating the same way, their common axis will tend to place itself in the magnetic meridian, like the axis of a magnet. Such a system was called by Ampère a solenoid (σωλην, a tube), and was realized by him in the following manner.

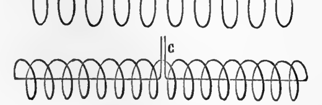


Fig. 514.—Solenoids.

Imagine a wire bent into such a shape as to consist of a number of rings united to each other by straight portions. It will differ from a theoretical solenoid only by having currents in these straight portions; but if the two ends of the wire be carried back till they nearly meet in the middle of the length, as shown at A and B (Fig. 514), the currents in these returning portions, being opposite to those in the other straight portions, will destroy their effect, and the resultant electro-dynamic action of the system will be simply due to the currents in the rings. The same effect is more conveniently obtained by substituting for the rings and intermediate straight portions, a helix, which, by the principles of sinuous currents, is equivalent to them. Each spire of the helix represents a circle perpendicular to the axis, together with a straight portion parallel

to the axis and equal to the distance between two spires. The effect of all the straight portions is exactly destroyed by the wires which return from the ends of the helix and meet in the middle. This arrangement, which is represented at C, is that which is universally adopted, the returning wires being sometimes in the axis, and sometimes on the outside of the helix.

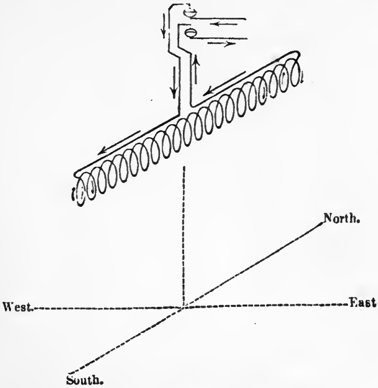


Fig. 515.—Orientation of Solenoid.

If a solenoid, thus constructed, be suspended on an Ampère's stand, as in Fig. 515, and a current sent through it, it will immediately place its axis parallel to a declination needle. It may accordingly be said to have poles. In Fig. 516, A represents the austral or north-seeking, B the boreal or south-seeking pole of the solenoid; that is to say, the direction of the current is against or with the hands of a watch according as the austral or boreal pole is presented to the observer. The same difference is illustrated by Fig. 515.

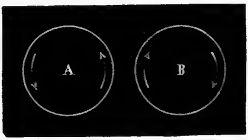


Fig. 516.—Poles of Solenoid.

791. Dip of Solenoid.—If a solenoid could be balanced so as to be perfectly free to move about its centre of gravity, it would place its axis parallel to the dipping-needle. The experiment would be scarcely practicable with a solenoid properly so called, on account of its weight; but it can be performed with a single plane circuit, such as that shown in Fig. 517. If such a circuit is nicely balanced about an axis through its centre of gravity, and placed so that it can turn freely in the plane of the magnetic meridian, the passing of a current through it will cause it to set its plane perpendicular to the direction of a dipping-needle. This effect is due to the action of terrestrial magnetism on the upper and lower sides of the rectangle. The plane of the rectangle is

represented in the figure as coinciding with the direction of dip. In this position the action of terrestrial magnetism urges the upper side backwards and the lower side forwards, and stable equilibrium will be attained when the rectangle has turned through 90°.

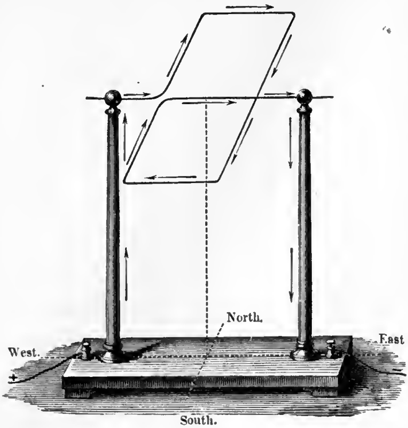


Fig. 517.—Dip of Element of Solenoid.

792. Mutual Actions of Solenoids.—Solenoids behave like magnets not only as regards the forces which they experience from terrestrial magnetism, but also as regards the actions which they exert upon one another. The similar poles of two solenoids repel, and the unlike poles attract each other, as we may easily prove by suspending one solenoid from an Ampère's stand and bringing another near it.

The reason of these attractions and repulsions is illustrated by Fig. 518. If two austral poles are placed opposite each other, as in the upper part of the figure, the currents are circulating round them in opposite directions, and, by the laws of parallel currents, should therefore repel each other; whereas if two dissimilar poles be placed face to face, the currents which circulate round them are in the same direction, and attraction should therefore ensue.

Fig. 518.—Mutual Action of Solenoids.

Lastly, if one pole of an ordinary magnet be brought near one pole of a suspended solenoid, as in Fig. 519, repulsion or attraction will be exhibited according as the poles in question are similar or dissimilar. In the position represented in the figure, this action is mainly due to the action of the boreal pole of the magnet upon the descending currents in the near side of the

solenoid. This action consists in a force to the left hand, nearly parallel to the axis of the solenoid, which tends to make the solenoid rotate about its supports, and thus to bring the end A of the solenoid into contact with the end B of the magnet.

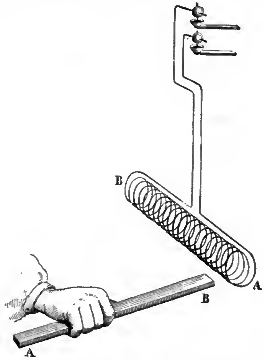


Fig. 519.—Action of Magnet on Solenoid.

It may be shown, by the aid of Ampère's formula for the mutual force between two elements, that the mutual action of two solenoids is equivalent to four forces, directed along lines joining the poles of the solenoids, and varying inversely as the squares of the distances between the poles; the forces between similar poles being repulsive, and the other two attractive. The analogy between solenoids and magnets is thus complete.

793. Astatic Circuits.—When it is desired to eliminate the influence of terrestrial magnetism in electro-dynamic experiments, an astatic circuit may be employed as the movable conductor. Two such circuits are represented in the accompanying figures (Figs. 520, 521). In each of them the current in one half of the circuit circulates

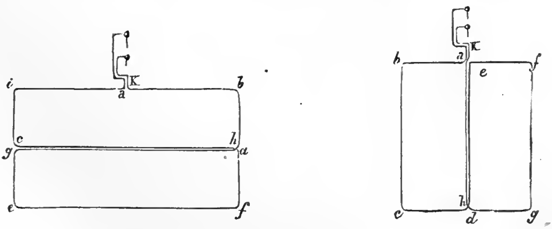
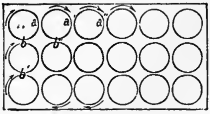


Fig. 520. Astatic Circuits. Fig. 521.

with, and in the other against the hands of a watch, thus producing equal and opposite tendencies to orientation, which destroy one another.

794. Ampere's Theory of Magnetism.—In accordance with the preceding facts, Ampère propounded the hypothesis that what is called magnetism consists in the existence of electric currents circulating

round the particles of magnetic bodies. In iron or steel, when unmagnetized, according to this theory, the currents around different particles have different directions; but when it is magnetized, the directions of all are the same. Fig. 522 represents an ideal section of a magnetized bar at right angles to the direction of its magnetiza-



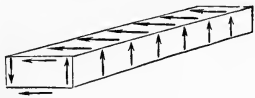


Fig. 522. Amperian Currents in Magnets. Fig. 523.

tion. On the neighbouring faces of any two particles, the currents are in opposite directions, hence, by the laws of sinuous currents, there is a mutual destruction of force through the whole interior, and the resultant effect is the same as if there were currents circulating round the exterior of the magnet, as represented in Fig. 523.

Magnetization by influence depends, according to this theory, on the tendency of currents to set themselves parallel and in similar directions; and if the substance magnetized possesses coercive force, the direction thus impressed on its currents persists after the influence is removed. In soft iron, on the contrary, they resume their former irregularity.

Ampère's theory of magnetism is in complete accordance with all known facts. But it admits of question whether it is simpler to deduce the laws of magnetism and electro-magnetism from those of electro-dynamics; or to adopt the reverse order, and deduce the laws of electro-dynamics from those of electro-magnetism.

795. Rotations of Magnets.—The following experiment is due to Ampère. A magnet, loaded with platinum at its lower end, floats upright in mercury contained in a glass vessel (Fig. 524). A cavity is hollowed out in the top of the magnet. This contains mercury, in which a point dips. On connecting one of the terminals of a battery with this point, and the other with the outer edge of the mercury in the vessel, the magnet is seen to rotate on its axis. If the north-seeking pole is uppermost, and the positive pole of the battery is connected with the point, the direction of rotation is N.E.S.W.

The Amperian explanation of this phenomenon is, that it is due

to the action between the outward-flowing current in the mercury and the Amperian currents which circulate round the magnet. The

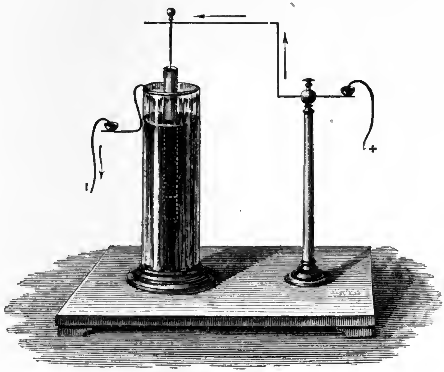


Fig. 524.—Rotation of Magnet.

latter, as represented by the arrows n C, C m in Fig. 525, are opposite to watch-hands. The outward-flowing current in C D attracts the current in C m, since they are both directed away from the angular point C, and repels the current in n C. Hence the magnet is made to rotate in the direction m C n, opposite to that of the Amperian current.

The experiment is sometimes varied by making the point dip in the mercury in the vessel, the magnet being allowed to float freely

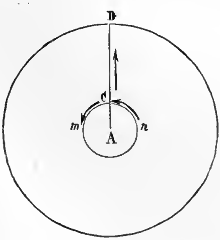


Fig. 525.—Explanation of Rotations.

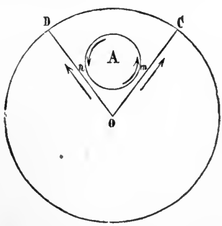


Fig. 526.—Explanation of Rotations.

near it, and a metallic ring being immersed at the outer edge of the mercury, to which the current flows out in all directions from the

point. As soon as the circuit is completed, the magnet begins to revolve round the point. The rotation will be in the same direction as in the other form of the experiment; that is to say, if the current flows outwards from the point to the edge of the vessel, the direction of rotation will be opposite to that of the Amperian currents in the magnet. This is easily explained by the laws of parallel currents, for the current in O C (Fig. 526) attracts the Amperian current at *m*, and the current in O D repels the current at *n*. The magnet will therefore move from O D to O C, and will revolve round O in the direction N.E.S.W.

796. Magnetization by Currents.—Ampère's theory of magnetism leads naturally to the conclusion that a bar of iron or steel may be magnetized by means of a current. Arago was the first to establish this fact, but without a clear apprehension of the conditions necessary for success, or of the criterion for determining which will be the austral, and which the boreal pole. Ampère conceived the idea of introducing the needle to be magnetized into the axis of a solenoid, and the result confirmed his prediction that the poles of the needle would be turned the same way as those of the magnetizing helix. This is what must happen if the currents in the helix force the Amperian currents in the bar into parallelism with themselves, so that all rotate the same way.

It is to be remarked that, in this process of magnetization, the portions of the currents parallel to the axis of the helix produce no effect. The wire through which the current is to be sent may be wound like thread upon a reel, returning alternately from end to end, and all the convolutions will contribute to magnetize the bar the same way, although it is evident that the helices are in this case alternately right-handed and left-handed. The north-seeking and south-seeking poles may be in all cases distinguished by the rule that the direction in which the current circulates in the coil is against watch-hands as seen from the former and with watch-hands as seen from the latter; or it may be remembered by the rule, that if I identify my own body in imagination with a portion of the wire, and suppose the current to enter at my feet, while my face is towards the needle, the north-seeking pole will be to my left. In 1 and 2 (Fig. 527), *a* will be the austral (or north-seeking), and *b* the boreal pole of the inclosed needle, when the current in the helix has the direction indicated by the arrows.

If the direction of winding is changed, in the manner represented

in 3, so that, as seen from one end, the direction in which the current circulates is in one part with and in another against the

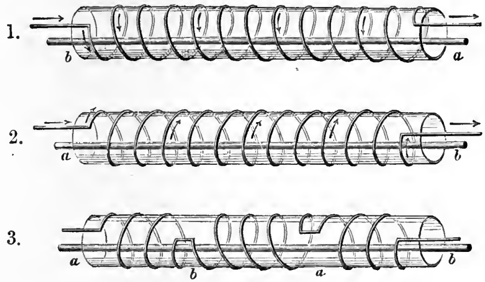


Fig. 527.

1. Right-handed Helix. 2. Left-handed Helix. 3. Arrangement for Consequent Points.

hands of a watch, consequent points (§ 689) will be formed at the points of change. Thus, if the current enters at the left-hand end of the coil, the points *a a* will be austral, and the points *b b* boreal poles.

797. Electro-magnets.—Arago was the first to observe the effect of a current in magnetizing soft iron. On plunging in iron-filings a wire through which a very strong current was passing, he observed that the filings clung to the wire, that they placed their length tangentially to it, and that they fell off when the current ceased to pass. Each filing was evidently, in this experiment, a little magnet placing itself at right angles to the current. A cylindrical bar of iron can be powerfully magnetized by wrapping round it a coil of insulated wire and sending a current through this coil. Stout copper wire is generally employed for this purpose. Such an arrangement is called an *electro-magnet.*

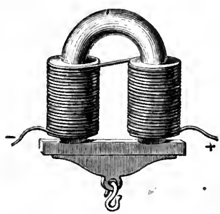


Fig. 528.—Horse-shoe Electro-magnet.

The bar has often the horse-shoe form, as in Fig. 528, and in this case the central part is usually left bare. The direction of winding on the ends must be such that, if the bar were straightened out, the current would circulate in the same direction round every part. This

is clearly shown in the figure. Electro-magnets have been constructed capable of sustaining a load of many tons.

Besides the enormous power that can be given them, electro-magnets have the advantage of being readily made or unmade instantaneously, by completing or interrupting the circuit to which the coil belongs. This principle has received very numerous and varied applications, some of which will be mentioned in later chapters.

798. Residual Magnetism.—When the current round an electro-magnet is interrupted, the destruction of the magnetization is not complete. The small remaining magnetization is called *remanent* or *residual* magnetism. It is frequently sufficiently powerful to retain the armatures in contact with the magnet, and thus necessitates the employment of *opposing springs,* if instantaneous separation is desired. The mere act of separation suffices to destroy the greater part of the residual magnetism.

Fig. 529 represents an electro-magnet E E′, furnished with an

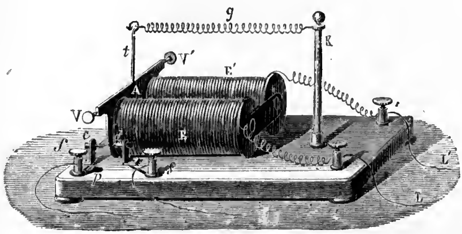


Fig. 529.—Electro-magnet with Opposing Spring.

opposing spring *g*. The armature A, with its lever *t*, turns about the axis V V′. The opposing spring *g* has one end fixed at K, and the other attached to the end of the lever *t*. It therefore tends to remove the armature from the magnet. *c* and *d* are two points whose distance can be regulated, and which serve to limit the movements of the armature.

CHAPTER LIX.

INDUCTION OF CURRENTS.

799. Induced Currents.—Induced currents may be described as currents produced in conductors by the influence of neighbouring currents or magnets. Their discovery by Faraday in 1831 constitutes an epoch in the history of electrical science. We shall first describe some modes of producing them; and then state their general laws.

800. Currents induced by Commencement and Cessation of Currents.—Let two coils be wound upon the same frame B, one of them, called

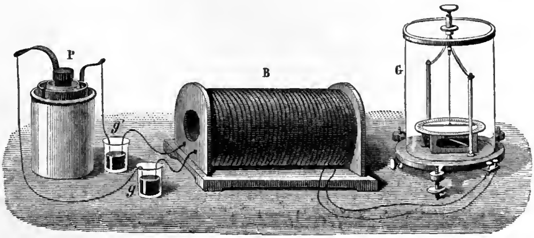


Fig. 530.—Current induced by Commencement or Cessation.

the secondary coil, having its ends connected with the binding-screws of the galvanometer G, while the ends of the other, which is called the primary coil, dip in two cups of mercury gg' connected with the two plates of the voltaic element P. As long as the current is passing steadily in the primary coil, the needle of the galvanometer remains undeflected; but if the current be stopped, by lifting a wire out of one of the mercury cups, the needle is immediately deflected, indicating the existence of a current in the same direction as that which

was previously circulating in the primary coil. This effect is very transitory. The needle appears to receive a sudden impulse which immediately passes away. If the current be then re-established, there is a deviation to the other side, indicating a current in the opposite direction to that in the primary coil; and this deviation, like that which occurred before, is merely the effect of an instantaneous impulse, the needle making a few oscillations from side to side, and then remaining steadily at zero. This experiment, which is substantially the same as that by which Faraday first made the discovery, establishes the following proposition:—*When a current begins to flow, it induces an inverse current in a neighbouring conductor; when it ceases, it induces a direct current; and both the currents thus induced are merely instantaneous.*

801. Currents induced by Variations of Strength of Primary Current.—Employing the same apparatus, let us, while the primary current

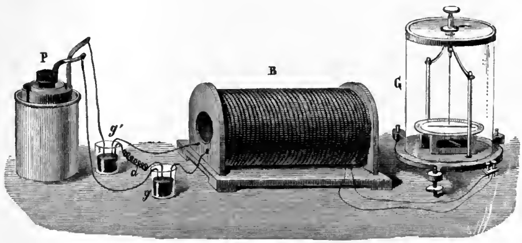


Fig. 531.—Current induced by Change of Strength.

is passing, connect the two mercury cups by the wire d (Fig. 531), thus dividing the circuit (§ 747), and causing a great diminution of the current in the primary coil. At the instant of making this connection, the needle of the galvanometer is affected, moving in the same direction as if the primary current were stopped; and on lifting the connecting wire out of one of the cups, so as to produce a sudden increase in the current in the primary coil, the needle moves in the opposite direction. *When a current receives a sudden increase, this produces an inverse current in a neighbouring conductor; and when it is suddenly decreased, a direct current is induced.*

802. Currents induced by Variations of Distance.—Currents may also be induced by change of distance between the primary and secondary conductors. Let the secondary coil, for example, be hollow,

as in Fig. 532, and let the primary coil, with the current passing in it, be suddenly introduced into its interior. The galvanometer will indicate the production of an inverse current in the secondary coil.

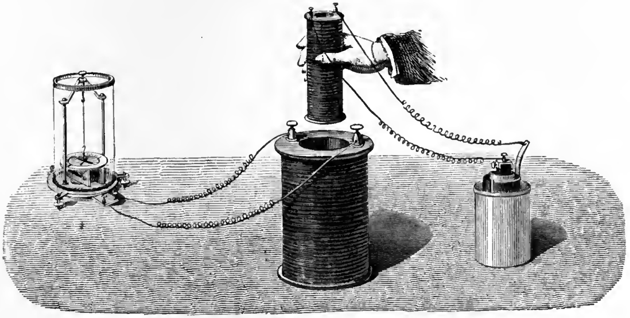


Fig. 532.—Current induced by Change of Distance.

When the needle has come to rest, let the primary coil be withdrawn, and a direct current will be indicated by the galvanometer. These currents differ from those previously mentioned in being less sudden. They last as long as the relative motion of the two coils continues. *When a conductor conveying a current approaches or is approached by a neighbouring conductor, an inverse current is induced in the latter; and when one of these conductors moves away from the other, a direct current is induced.*

Fig. 533.—Current induced by Motion of Magnet.

803. Magneto-electric Induction.—As a current may be regarded as a magnet (§ 711), and a magnet may be regarded as a system of currents (§ 794), induction can be effected by a magnet as well as by a coil.

Let a hollow coil be connected with a galvanometer, and a magnet held over it, as in Fig. 533. As long as the magnet remains stationary, no current is indicated; but when one pole of the magnet is thrust into the interior of the coil, the needle is deflected by an impulse which lasts only as long as the motion of the magnet. If the magnet is

allowed to remain at rest in this position, the needle, as soon as it has time to recover from its oscillations, stands at zero; but on withdrawing the magnet, another current will be indicated in the opposite direction to the former.

Currents may also be induced, with even more striking effect, by moving one pole of a magnet towards or from one end of a soft-iron bar previously placed in the interior of the coil (Fig. 534). These

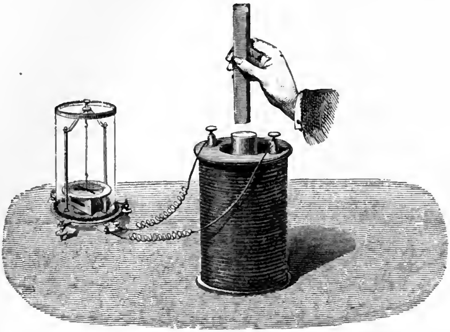


Fig. 534.—Current induced by Magnetization of Soft Iron.

currents are due to the magnetism produced and destroyed in the soft iron. *When the intensity of magnetization of a piece of iron or steel undergoes changes, currents are induced in neighbouring conductors.* The directions of these currents can be inferred from the preceding rules by supposing a solenoid to be substituted for the magnet.

804. Lenz's Law.—*The currents induced by the relative movement either of two circuits or of a circuit and a magnet are always in such directions as to produce mechanical forces tending to oppose the movement.* For example, when two parallel wires, through one of which a current is passing, are made to approach, an opposite current is induced in the other; and opposite currents by their mutual repulsion resist approach. This general law as to the direction of induced currents was first distinctly enunciated by Lenz, a Russian philosopher.

805. Direction of Induced Currents specified by Reference to Lines of Magnetic Force.—We have already mentioned, in connection with the mutual forces between magnets and currents (§ 712), that a

wire conveying a current experiences force perpendicular to its length, and at the same time perpendicular to the lines of magnetic force, when placed in a magnetic field. We have seen that, if the current is from foot to head, and the lines of force (for an austral pole) run from front to back, the force experienced by the wire is a force to the right. Motion of the wire to the right will diminish this force by diminishing the current, motion to the left will increase it by increasing the current, and the amount of increase or diminution is quite independent of the original amount of current. Let the direction of the lines of magnetic force for an austral pole be called *from front to back;* then the motion of a conductor *to the right* generates a current in it *from head to foot,* and motion in the opposite direction generates an opposite current. We shall have frequent occasion to recur to this criterion of direction, which applies to every case of induced currents.

As the generation of currents by induction depends not on absolute but on relative motion, namely the relative motion of the conductor and the lines of magnetic force, the criterion of direction will take the following form when the conductor is supposed to be stationary, and the lines of force to move.[1] Let the direction of the lines of magnetic force for an austral pole be called *from front to back,* then *if the lines of force move so as to cut through the conductor from right to left, a current will be induced in the conductor from head to foot.*

If the conductor forms part of a closed circuit, we shall have a continuous current flowing through it as long as the motion lasts. If the circuit is open, there will merely be an incipient current, which, if its direction be from head to foot, will reduce the end of the conductor which we are regarding as its foot to a higher electrical potential than the other, and this difference of potential will be maintained as long as the motion lasts.

806. Quantitative Statements.—In order to state the quantitative laws of induced currents in the simplest and most general manner, we must employ the conception of tubes of force as explained in § 607 (but they will now be tubes not of electrical but of magnetic force), and we must suppose them to be arranged in the equable manner described in § 608. That is to say, we must suppose the

[1] It may be noted that when a bar-magnet is rotated on its axis, it induces no current in a neighbouring wire, inasmuch as its lines of force cut such a wire once positively and once negatively.

whole field cut up into tubes of force in such a manner that, if a cross section (an equipotential surface as regards magnetic potential) be made in any part of the field, the number of tubes per unit of sectional area is equal to the intensity in that part of the field. It is more usual to speak of *number of lines of force* than of *number of tubes*, the convention being that each tube contains one line; but the counting of tubes rather than lines has the advantage of naturally allowing fractional parts to be reckoned, and not suggesting the idea of discontinuity.

The tubes of force due to a magnet are to be regarded as rigidly attached to the magnet, and carried with it in all its movements. whether of translation or rotation. They undergo no change of size or form unless the magnet itself undergoes changes in its magnetization.

These conceptions being premised, the quantitative laws of induced currents can be stated with great simplicity and complete generality.

1. When a conductor is moved in a magnetic field, the ELECTROMOTIVE FORCE generated by the motion is equal to the number of tubes which the conductor cuts through per unit time.

2. If the conductor forms part of a closed circuit, the CURRENT generated in the circuit is the quotient of the number of tubes cut through per unit time, by the resistance of the circuit; and, lastly,

3. The whole QUANTITY of electricity conveyed by the current is the quotient of the number of tubes cut through, by the resistance of the circuit. The quantity of electricity conveyed by a current of brief duration is measured by observing the swing of a galvanometer needle (§ 722). It is proportional to the greatest deviation of the needle from zero, provided that this deviation is small, and that the duration of the current is less than that of the swing. When experiments on induced currents are made under these conditions, it is found that the deviation of the needle depends only on the initial and final positions of the body which is moved, being independent both of the path taken and of the velocity.

The dependence of the quantity of electricity induced upon the number of tubes cut through, was discovered by Faraday, who established it experimentally by moving a loop of wire in various ways in the vicinity of a magnet. The three foregoing laws were all, in fact, substantially established by the series of researches in which these experiments occur.[1]

[1] *Researches*, vol. iii. series xxviii.

In counting the tubes cut through, it is necessary to attend to the direction of the current due to the cutting of each tube. Those tubes which are so cut as to give currents in one direction round the circuit (when tested by the criterion of § 805) must have one sign given them, and those which give currents in the opposite direction must be reckoned as of the opposite sign. It is in every case the algebraic sum that is to be taken; and if a tube is cut once positively and once negatively, it may be left out of the reckoning.

807. Deduction of the Laws from Electro-dynamic Principles.—The laws in the preceding section are deducible by the principle of energy from Maxwell's rule (§ 788), which asserts that the mechanical work requisite to produce a given displacement of a circuit in a magnetic field is equal to the strength of the current multiplied by the number of tubes of force cut through. Call this number n and the current C. Then, if there is no other electro-motive force in the circuit beside that which is due to the motion, the work C n must be equal to the energy of the current, which is $\mathrm{E\,C}\,t$. t denoting the time. Hence we have

$$\mathrm{E}=\frac{n}{t}$$

that is, the electro-motive force is equal to the number of tubes cut through per unit time.

If the circuit contains a battery of electro-motive force E_0, the energy supplied by this battery is $\mathrm{E}_0\,\mathrm{C}\,t$; hence we have

$$\mathrm{E\,C}\,t=\mathrm{E}_0\,\mathrm{C}\,t+\mathrm{C}\,n,$$

Or

$$\mathrm{E}=\mathrm{E}_0+\frac{n}{t},$$

that is, the electro-motive force $\mathrm{E}-\mathrm{E}_0$ produced by the motion is equal to the number of tubes cut through per unit time; and these are to be counted as positive when the direction of the motion is opposed to the forces of the field, since we have supposed positive work to be supplied. The induced current is therefore *with* or *against* the original current according as the motion is *against* or *with* the mutual forces between the current and the field.

808. Tubes of Force for Resultant and Components.—The principle of superposition can be applied to tubes of force. For if we resolve the whole force into any two components, these three forces will be represented by the three sides of a triangle as in Fig. 535, where B C represents the resultant, and B A, A C the two components.

By producing each side, and drawing a parallel to it through the opposite angle, we obtain longitudinal sections of three tubes, whose cross sections are proportional to the perpendiculars on the sides of the triangle A B C from the opposite angles. These perpendiculars are inversely as the sides (since side $\times$ perpendicular $=$ double area of triangle). Hence the cross sections of the three tubes are inversely as the forces, and the number of tubes per unit area of cross section will be directly as the forces.

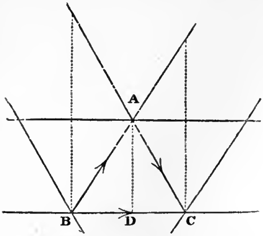


Fig. 535.—Superposition of Tubes.

In moving parallel to B C, no resultant tubes are cut, and as many component tubes are cut from the right to the left as from the left to the right of a person travelling with the component forces. In moving perpendicular to B C, through a distance equal to A D the perpendicular from A on B C, the fraction $\frac{BD}{BC}$ of one component tube is cut, and the fraction $\frac{DC}{BC}$ of another, the sum of these fractions being unity. Hence, in every motion, *the number of component tubes cut* (reckoned algebraically) *is equal to the number of resultant tubes.*

In dealing with terrestrial magnetism, it is often convenient to consider separately the tubes of vertical and of horizontal force; for example, effects depending only on horizontal force can be determined by considering the horizontal tubes alone.

809. Uniform Field.—In a field of uniform intensity the lines of force cannot be curved, for if they were, the equipotential surfaces, which cut them at right angles, would not be equidistant, but would be nearer together on the side next the centres of curvature than on the opposite side, and the force would be greatest where these surfaces were nearest (§ 604). The lines of force in a field of uniform intensity are therefore straight; and, since the tubes of force must have a constant cross section (§ 607), these tubes must be cylinders or prisms, and the lines of force parallel. A field of uniform intensity of force is therefore also uniform as regards direction of force.

The electro-motive force generated by the motion of a straight wire of length L in a field of uniform intensity I, with a velocity of translation V, being equal to the number of tubes cut through in unit time, will be L V I, if the length of the wire and the direction of

motion are perpendicular to each other and to the lines of force. For any other position of the wire, and for any other direction of motion, the number of tubes cut through will evidently be less. If the length of the wire is parallel to the lines of force, no tubes will be cut through, whatever be the direction of motion; and if the direction of motion be parallel to the lines of force, no tubes will be cut through, whatever be the position of the wire. In these two cases, then, there is no generation of electro-motive force tending to produce a current along the wire.

Terrestrial magnetism furnishes us with an example of a uniform field, so long as we confine our attention to a space of moderate dimensions, such as the interior of a room.

810. Movement of Lines of Force with Change of Magnetization.—As long as a piece of iron or steel remains unchanged in its magnetization, its tubes of force are to be conceived of as a rigid system rigidly connected with it. When the intensity of magnetization is increased, new tubes are added and the old ones are crushed together. The new tubes are to be regarded as coming into existence at the magnetic axis of the magnet, and pushing the old ones further away from the axis. When the intensity of magnetization falls off, a reverse motion occurs, and the axis absorbs those tubes which lie next it.

Similar remarks apply to changes of strength in a current. The lines of magnetic force due to a current in a straight wire are circles, and the tubes of force are rings, having the wire for their common axis. When the current receives an increase of strength, the new rings must all be conceived of as starting from the wire, and pushing out the old rings before them, and on the diminution or cessation of the current a reverse movement occurs.

When a current suddenly commences in a wire, or a piece of soft iron is suddenly magnetized, the effect upon a neighbouring conductor is the same (so far as this source of magnetic force is concerned) as if the conductor were suddenly moved up from a great distance into its actual position. The experimental results described in §§ 800–803 are thus only particular cases of the general principles of §§ 805, 806.

811. Unit of Resistance.—Units of *length, mass,* and *time,* having been selected, unit *force* is defined as that which, acting on unit mass for unit time, generates unit velocity.

A magnetic pole of unit strength, or a unit *pole,* is defined as that

which attracts or repels an equal pole at unit distance with unit force.

Unit *intensity of field* is defined as the intensity at a place where a unit pole experiences unit force.

A unit *current*, or a current of unit strength, is one which, for each unit of its length, affects a unit pole at unit distance with unit force. In passing through a circular coil of unit radius and length l, the force which it exerts on a unit pole at the centre is l.

Unit *electro-motive force* is the electro-motive force existing in a circuit in which unit current does unit work in each unit of time; and unit *resistance* is the resistance of a circuit in which unit electro-motive force would produce unit current.

The course of the above investigation shows that the units of length, mass, and time are sufficient to determine all the other units mentioned. It can be further shown[1] that the unit of resistance is independent of the unit of mass, and depends only on the units of length and time, being directly as the unit of length, and inversely as the unit of time—a property which is also characteristic of the unit of velocity. Hence a resistance, like a velocity, can be adequately expressed in *metres per second*. The unit of resistance now commonly employed is the *ohm*, which is defined as *ten million metres per second*. The resistance of a Daniell's cell of the Post-office pattern is about 20 ohms. The resistance of a mile of submarine telegraph-cable is from 4 to 12 ohms.

812. Induction by means of Terrestrial Magnetism.—If a wire ring, or any other form of closed circuit, receives a movement of translation in a uniform field, no current is generated, because the same number of force-tubes are cut negatively as positively. Whatever currents are generated by the motion of a closed circuit in the terrestrial magnetic field, must therefore be due solely to rotational movements. Suppose the circuit to consist of a single circle of wire, and let it be initially placed so that its plane is perpendicular to the dipping-needle, and therefore perpendicular to the lines of magnetic force. In this position, the number of force-tubes which it incloses is equal to the product of the inclosed area by the total intensity of terrestrial magnetic force, that is to $\pi r^2 \mathrm{I}$, I denoting this intensity, and r the radius of the circle. Now let the ring rotate through 180° about any diameter, so that it comes back into its original place, but facing the opposite way. During this semi-revolution, each half of

[1] See Appendix at the end of this Part.

the ring has cut through all the tubes which passed through the ring, and though in one sense the two halves have been cutting the tubes in opposite directions, the application of the criterion of § 806 shows that the resulting currents are in the same direction round the circuit. The number of tubes cut through is therefore to be reckoned as $2\pi r^2 I$, and the quotient of this by the time occupied in a semi-revolution is the average electro-motive force (§ 809). If the rotation be uniform, the actual electro-motive force is greatest in the middle of the semi-revolution, and is zero at its commencement and termination. During the other half-revolution the circumstances are precisely the same, except that the two halves of the ring have changed places. If we compare the currents in two positions of the ring which differ by 180°, we see that the current round the ring has the same direction in space, but opposite directions as regards the ring itself.

If, instead of a single ring of wire, we have a circular coil consisting of any number of convolutions, with its two ends united, the same principles apply. If there are n convolutions, the electro-motive force will be n times greater than with one, but as the resistance is also n times greater the strength of current is the same.

In the apparatus called *Delezenne's Circle*, a coil of wire revolves about a diameter, but the two ends of the coil, instead of being directly united, are so connected with the two ends of the axis of rotation that the circuit is completed through a galvanometer. On rotating the coil rapidly by means of a handle provided for the purpose, a current is indicated by the galvanometer, and this current is found to be strongest (for a given rate of rotation) when the axis is perpendicular to the dipping-needle. If the axis is inclined at an angle θ to the dipping-needle, the current is proportional to $\sin\theta$; and if the axis is parallel to the dipping-needle there is no current at all. For a given position of the axis, the current varies directly as the speed of rotation. When the time of a revolution is only a small fraction of the time in which the needle would oscillate, the variations of electro-motive force, and consequently of current, which take place during a revolution, have not time to manifest themselves, and the deflection of the needle is that due to the average current. It is necessary, however, that a commutator be employed to prevent the reversal of the current at each half-revolution. The proportionality of the current to $\sin\theta$ is easily inferred from the principles of the foregoing sections; for if the plane of a circle, instead of being per-

pendicular to the lines of force, is inclined to them at an angle θ, the number of force-tubes which it incloses will be not $\pi r^2 I$, but $\pi r^2 I \sin \theta$.

813. British Association Experiment.—The first experiments for constructing a coil whose resistance should be a known number of metres per second, were conducted by a committee of the British Association in 1862. A circular coil of wire, with its ends joined, was made to revolve rapidly, at a measured rate, about a vertical axis; and the current induced was measured by the deflection of a magnetized needle suspended, within a glass case, in the centre of the coil. The part of the earth's magnetic force which comes into play in this arrangement, is only the horizontal component, and it is worthy of remark that variations in the horizontal intensity do not alter the deflection of the needle, since they affect to the same extent the amount of the induced current, and the terrestrial couple on the needle tending to resist deflection.

All the other elements involved were determined by observation, and hence the value of R in metres per second was calculated. By comparing the resistances of other coils with that of the coil used in this experiment (a comparison which can be made with great accuracy by means of Wheatstone's bridge), their values in metres per second were at once determined; and it was easy to construct a resistance-coil of ten million metres per second, or any other desired amount of resistance. As the resistances of metals are increased by heat, a standard coil can only be correct at one particular temperature.

814. Induction of a Current on Itself: Extra Current.—If two portions of the same wire are side by side, the sudden commencement or cessation of a current in one, induces a current in the other, just as if they were portions of two unconnected circuits. An action of this kind occurs whenever a current commences or ceases in a coil, each convolution exercising an inductive influence on the rest. This action is called the *induction of a current upon itself,* and the current due to it is called an *extra current.*

The extra current on the commencement of the primary current is inverse, and merely acts as a hinderance to commencement; but the extra current on the stoppage of the primary current is direct, and is often a strongly-marked phenomenon. Hence it is that, with batteries of ordinary power, a spark is obtained on breaking, but not on making connection. The spark is particularly brilliant when a coil of many convolutions is included in the circuit, and especially if

this coil incloses a core of soft iron. If an observer holds in his hands two metallic handles permanently connected with the two ends of such a coil, and if the circuit of the battery is alternately made and broken, he will receive a shock from the extra current at each interruption. If the interruptions succeed each other rapidly, the physiological effect may become very intense. Many of the machines employed for medical purposes are constructed on this plan.

Special contrivances are provided for producing a rapid succession of interruptions at regular intervals. They are called *rheotomes* or *contact-breakers*. Sometimes they consist of toothed wheels turned by hand,—sometimes of vibrating armatures moved automatically.

815. Ruhmkorff's Induction-coil.—Induced currents capable of producing very striking effects are furnished by the apparatus first successfully constructed by Ruhmkorff, and hence known as Ruhmkorff's coil.

It contains two coils of wire, one of them forming part of the circuit of a battery, and called the primary coil; while in the other, called the secondary coil, the induced currents are generated. In the axis of the coils is a bundle of stout straight wires of soft iron, with a disc of the same material at each end, to which the wires are united. Around this core is wound the primary coil, consisting of a copper wire about two millimetres in diameter. The ends of this wire are shown at f and f'. The secondary coil consists of much finer wire (about a quarter of a millimetre in diameter) and of much greater length. In large instruments the primary coil may have a length of 80 metres, and the secondary a length of 150 kilometres (94 miles). Special precautions must be taken to insulate the different convolutions of the secondary coil from one another, and from the primary coil. The two ends of the secondary wire are at the binding-screws A, B, which are supported on glass pillars. It is obvious that if currents are alternately passed and stopped in the primary coil, there will be an alternate generation of currents (or at all events of electro-motive forces) in opposite directions in the secondary coil. The action of the core is similar to that of the soft-iron bar in Fig. 534, and its inductive effect is always in the same direction as that of the primary coil, for the primary coil may itself be regarded as a temporary magnet with its poles turned the same way as those of the core.

The two ends of the primary coil are in connection with the two

coatings of a condenser of the kind described in § 628, stowed away in the flat wooden stand which forms the base of the instrument. It serves to mitigate the intensity of the extra-current in the primary coil at breaking circuit, some of the electricity rushing into the condenser instead of assisting to produce a spark at the place where the break occurs.

The successive makes and breaks are effected automatically in various ways. In small instruments the arrangement adopted is usually the same as that of the vibrating alarum described in § 840,

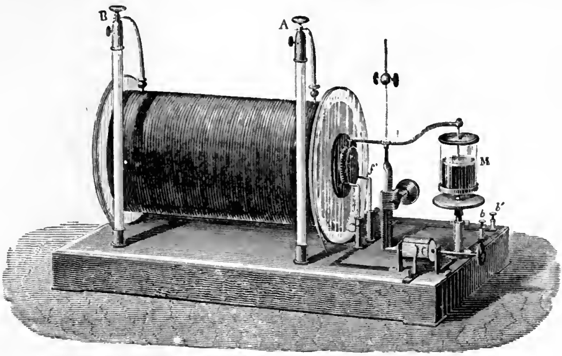


Fig. 536.—Ruhmkorff's Coil.

but for large instruments Foucault's contact-breaker is preferred. It is represented in its place in Fig. 536.

The wires from the battery are attached at b and b'. The current, entering for example at b, passes to the commutator C, and thence, through a brass bar let into the table, to the end f of the primary coil. Having traversed this coil, it comes out at f', and is conducted to a vertical pillar, carrying at its upper end a spring, to which the transverse lever L is attached. One end of the lever carries a point which just dips in the mercury of the vessel M, the bottom of which is metallic, and is in communication with b'. The other end of the lever carries a small armature of soft iron just above the end of the core.

When the current passes, the core becomes magnetized and attracts this armature, thus lifting the point at the other end of the lever out of the mercury and breaking circuit. The core being thus

demagnetized, the elasticity of the spring releases the armature, and the point again dips in the mercury, and completes the circuit. A thin layer of absolute alcohol is usually poured on the surface of the mercury, and serves, by its eminent non-conducting power, to make the interruptions and renewals of the current more sudden.

The *commutator* C serves to stop the current from passing or to make it pass in either direction, at pleasure. It is represented in end view and bird's-eye view in the two parts of Fig. 537. There is a cylinder of insulating material, turning by means of metallic axle-ends on metallic supports connected with the two ends of the primary coil. One axle-end is permanently connected by means of the screw *g* with the brass plate C on the surface of the cylinder, and the other axle-end is in like manner connected with the plate C′ diametrically opposite to C. The contact-springs *ff′* are in permanent connection with the two binding-screws A A′ which receive the wires from the battery. When *f* presses against C, and *f′* against C′, as shown in the figure, A is connected with one end of the primary coil and A′ with the other; and when the commutator is turned (by its milled head) through 180°, these connections will be reversed. If it is turned through 90°, the connections will be interrupted, as the contact springs will bear against insulating portions of the cylinder. The milled head is, of course, insulated from the axle-ends so as to protect the operator.

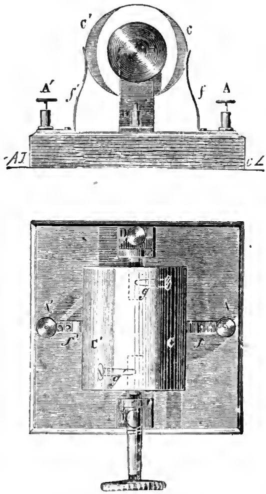


Fig. 537.—Commutator.

816. Spark from Induction-coil.—When the ends of the secondary coil are connected, currents traverse it alternately in opposite directions, as the primary circuit is made and broken. These opposite currents convey equal quantities of electricity, and if they are employed for decomposing water in a voltameter, the same proportions of oxygen and hydrogen are collected at both electrodes. If, however, the ends are disconnected, so that only disruptive discharge can

occur between them, the inverse current, on account of its lower electro-motive force, is unable to overcome the intervening resistance, and only the direct current passes (that is, the current produced by breaking the primary circuit). The sparks are usually from 1 inch to about 18 inches long, according to the size and power of the apparatus, and exhibit effects comparable to those obtained by electrical machines. A Leyden battery may be charged, glass pierced, or combustible bodies inflamed.

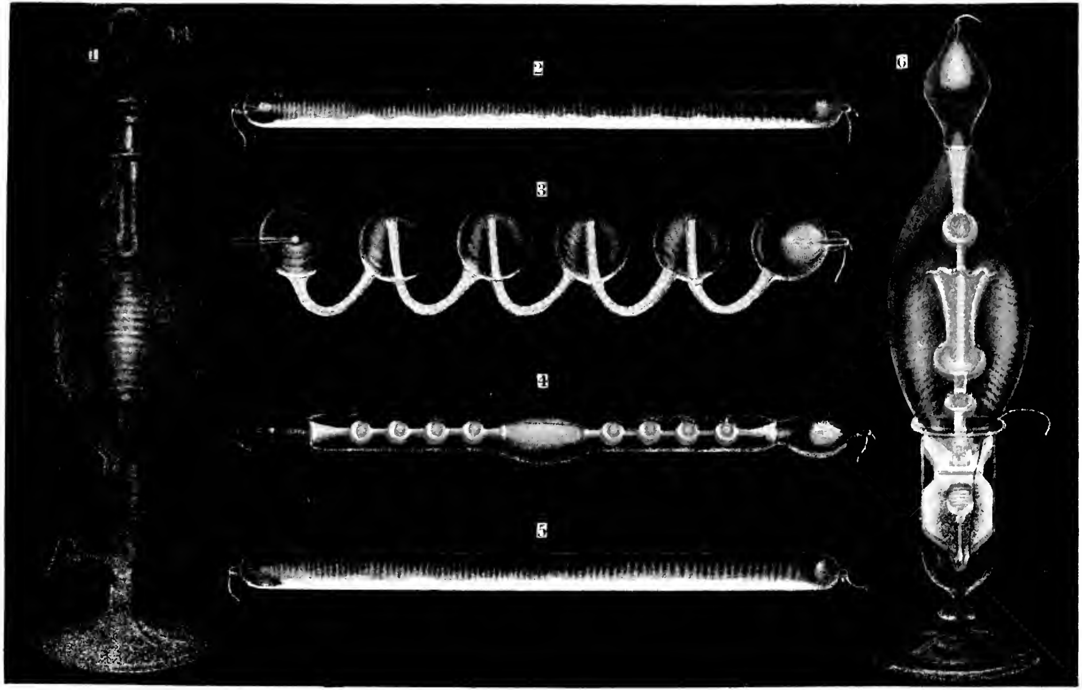
The great electro-motive force of the induced current, which enables it to produce these striking effects, depends on the great number of convolutions of the secondary coil, and on the suddenness of the interruptions of the primary current. The average electro-motive force is the product of the number of convolutions by the number of tubes of force which cut through them, divided by the time occupied (§ 806).

Fig. 538.
Statham's Fuse.

The discharges from a Ruhmkorff's coil become more violent and detonating if the two electrodes of the secondary coil are connected respectively with the two coatings of a Leyden jar, but the length of the spark is very much diminished.

Induction-coils are often used for firing mines, by means of Statham's fuse, which is represented in the annexed figure (Fig. 538). Two copper wires covered with gutta-percha have their ends separated by a space of a few millimetres, and inclosed in a little cylinder of gutta-percha containing sulphuret of copper. This, again, is inclosed in a cartridge, C D, which is filled up with gunpowder. The two wires are connected with the two ends of the secondary coil, and when the instrument is set in action, sparks pass between the ends A, B, heating the sulphuret of copper to redness, and exploding the powder.

817. Discharge in Rarefied Gases.—When the ends of the secondary coil are connected with the electrodes of the electric egg (Fig. 539), which has first been exhausted as completely as possible by the air-pump, a luminous sheaf, of purple colour, is seen extending from the positive ball to within a little distance of the negative ball. The latter is surrounded by a bluish glow. The blue and purple lights are separated by a small interval of darkness. If other gases are used instead of air, the tints change, but there is always a decided



ELECTRIC DISCHARGE IN RAREFIED GASES.

difference of tint between the positive and negative extremities. By the aid of the commutator it is easy to reverse the current, and thus produce at pleasure an interchange of the appearances presented by the two terminals.

Fig. 539.—Electric Egg.

If, before exhausting, we introduce into the egg a little alcohol, turpentine, or other volatile liquid, the light presents a series of bright bands alternating with dark spaces. Plate II. fig. 1 represents these stratifications as seen in vapour of alcohol.

The phenomenon of stratification is seen to more advantage in long tubes than in the electric egg; and the presence of alcoholic or other vapour may be dispensed with if the exhaustion be carried sufficiently far, as in the tubes constructed by Geissler of Bonn, which contain various gases very highly rarefied, and have platinum wires sealed into their extremities to serve as electrodes. Four such tubes are represented in Plate II. Certain substances, such as uranium glass, and solution of sulphate of quinine, become luminous in the presence of the electric light, and are called *fluorescent*. Such substances are often introduced into Geissler's tubes, for the sake of the brilliant effects which they produce.

818. Experiments of Gassiot and De La Rue.—By means of a battery of some thousands of cells, discharge in rarefied gases can be obtained without the use of an induction-coil, and with the advantage of greater steadiness. This has been done by Mr. Gassiot, and on a larger scale by Mr. De La Rue. The stratifications are still observed, and appear absolutely fixed in position to the naked eye. When examined by a revolving mirror they are found to exhibit the appearance of a rapid succession of discharges.

Mr. De La Rue's battery consists of 11,000 small chloride of silver cells; and when all the cells are used, a steady stream of fire passes between the terminals as soon as they are brought within about half an inch of each other, in air at atmospheric pressure.

819. Action of Magnets on Currents in Rarefied Gases.—The luminous discharges in Geissler's tubes exhibit the properties of currents. They are capable of deflecting a magnetized needle, and are themselves acted on by magnets, as in the following experiment. A soft-iron rod (Fig. 540) is fitted in the interior of a glass vessel from which the air can be exhausted, and is coated with an insulating substance to prevent discharge between it and a metallic ring which surrounds it near its lower end. When the terminals of a battery are connected, one with this ring, and the other with the upper end of the apparatus, a luminous sheaf extends from the summit towards the wire ring, and surrounds the soft iron. If, while things are in this condition, we place beneath the apparatus one pole either of a permanent magnet or an electro-magnet, the soft-iron rod is magnetized, and the luminous streaks immediately begin to revolve round it, the direction of rotation being always in accordance with the rule of § 712.

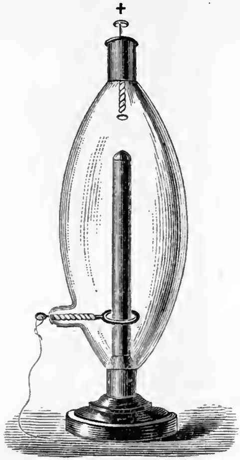


Fig. 540.—Action of Magnets on the Discharge.

820. Magneto-electric Machines.—Faraday's discovery of the induction of currents by magnets, was speedily utilized in the construction of magneto-electric machines, which, without a battery, and with no other stimulus than that afforded by the presence of a permanent magnet, enable the operator, by the expenditure of mechanical work, to obtain powerful electrical effects. The first machine of this kind was constructed in 1833 by Pixii. A magnet A was made to revolve close to a double coil BB′ (Fig. 541), in which a current was thus generated. The construction was improved by Saxton, and afterwards by Clarke, who made the magnet fixed, and caused the coil, which is much lighter, to rotate in front of it. Clarke's machine is extremely well known, being found in nearly all collections of physical apparatus.

821. Clarke's Machine.—In this machine there is a compound horse-shoe magnet fixed to a vertical support. Close in front of the

magnet, near its poles, are two connected coils *t, t'*, each containing a soft-iron core. The two cores are united by a plate of copper on the side next the magnet, and by a plate of soft iron on the remote side. The direction of winding in the two coils is the same as for an ordinary horseshoe electro-magnet. The coils are mounted on an axis *f*, which passes through the support of the steel magnet, and carries a pinion. By means of an endless chain passing over this pinion,

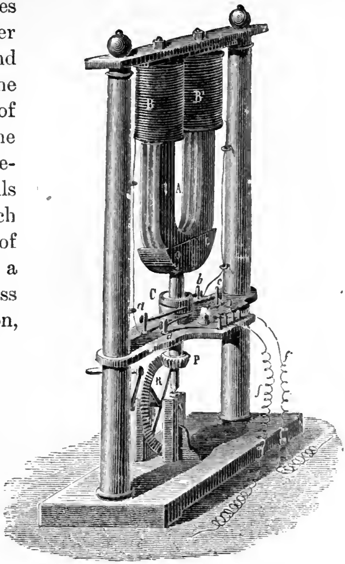


Fig. 541.—Pixii's Machine.

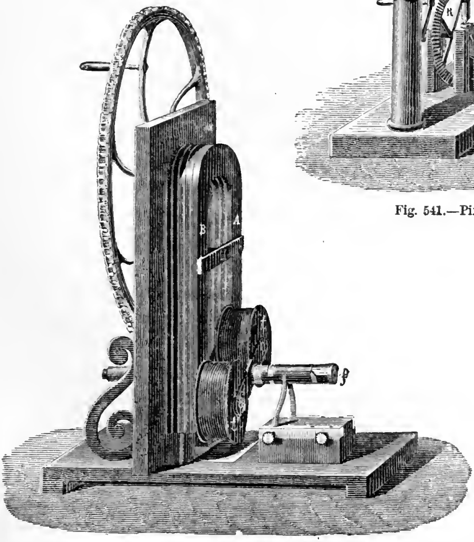


Fig. 542.—Clarke's Machine.

and over a large wheel to which a handle is attached, the pinion, and with it the coils, can be made to revolve rapidly. The

ends of the wire which forms the two coils are connected respectively with the two metallic pieces E, E′ (Fig. 543), which are mounted on the axis, but insulated from it and from each other.

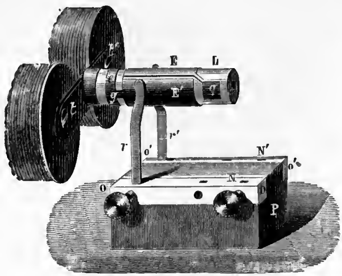


Fig. 543.—Commutator of Clarke's Machine.

Let us now examine the formation of the currents. The two iron cores, with their connecting iron plate, may be regarded as a temporary horse-shoe magnet, whose poles are always of opposite name to those of the steel magnet which are respectively nearest to them. The intensity of magnetization is greatest when the soft-iron magnet is horizontal, vanishes when it is vertical, and in passing through the vertical position undergoes reversal. If we call one direction of magnetization positive and the opposite direction negative, the strongest positive magnetization corresponds to one of the two horizontal positions, and the strongest negative to the other, the two positions differing by 180°. While the magnet, then, is revolving from one horizontal position to the other, its magnetization is changing from the strongest positive to the strongest negative, and this change produces a current in one definite direction in the surrounding coil. During the next half-revolution the magnetization is again gradually reversed, and an opposite current is generated in the coil. If we examine the direction of the currents due to the cutting across of the lines of force of the permanent magnet by the convolutions of the coil, we shall find that they concur with those due to the action of the cores. The current in the coils circulates in one direction as long as the electro-magnet is moving from one horizontal position to the other, and changes its direction at the instant when the cores come opposite the poles of the steel magnet.

By the aid of the commutator represented in Fig. 543, the currents may be made to pass always in the same direction through an external circuit. r and r' are two contact-springs bearing against the two metal pieces E, E′, which are the terminals of the coil. At the instant when the current in the coil is reversed, these springs are in contact with intermediate insulating pieces which separate the metallic pieces E, E′. When the current in the coil is in one direc-

tion (say from E to E′), r is in contact with E, and r' with E′. When the current in the coil is in the opposite direction (E′ to E), r is in contact with E′, and r' with E; thus in each case r is the positive and r' the negative spring, and the current will be from r to r' in an external connecting wire. O O, O′O′, are metallic pieces insulated from each other, and connected with the springs $r\,r'$ respectively. Binding-screws are provided for attaching wires through which the current is to be passed.

With this machine water can be decomposed, wire heated to redness, or soft iron magnetized; but these effects are usually on a small scale on account of the small dimensions of the machine.

For giving shocks, two wires furnished with metallic handles are attached to the binding-screws, and a third spring is employed which puts the terminals EE′ in direct connection with each other twice in each revolution, by making contact with two plates q. When these contacts cease, the current is greatly diminished by having to pass through the body of the person holding the handles, and the extra-current thus induced gives the shock. To obtain the strongest effect, the hands should be moistened with acidulated water before grasping the handles.

822. Magneto-electric Machines for Lighthouses.—Very powerful effects can be obtained from magneto-electric machines of large size driven rapidly. Such machines were first suggested by Professor Nollet of Brussels; and they have been constructed by Holmes of London and the Compagnie l'Alliance of Paris. It is by means of these machines that the electric light is maintained in several lighthouses; they have also been employed to some extent in electro-metallurgy. Fig. 544 represents the pattern adopted by the French company. It has eight rows of compound horse-shoe magnets fixed symmetrically round a cast-iron frame. They are so arranged that opposite poles always succeed each other, both in each row and in each circular set. There are seven of these circular sets, with of course six intervening spaces. Six bronze wheels, mounted on one central axis, revolve in these intervals, the axis being driven by steam-power transmitted by a pulley and belt. The speed of rotation is usually about 350 revolutions of the axis per minute. Each of the six bronze wheels carries at its circumference sixteen coils, corresponding to the number of poles in each circular set. The core of each coil is a cleft tube of soft iron, this form having been found peculiarly favourable to rapid demagnetization.

Each core has its magnetism reversed sixteen times in each revolution, by the influence of the sixteen successive pairs of poles between which it passes, and the same number of currents in alternately

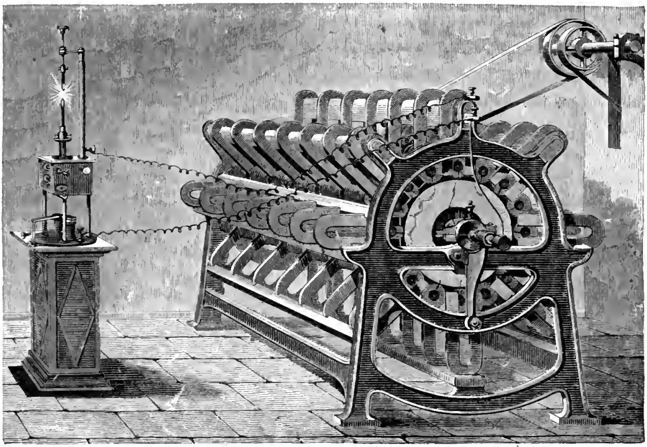


Fig. 544.—Lighthouse Machine.

opposite directions are generated in the coils. The coils can be connected in different ways, according as great electro-motive force or small resistance is required. The positive ends are connected with the axis of the machine, which thus serves as the positive electrode, and a concentric cylinder, well insulated from it, is employed as the negative electrode.

When the machine is employed for the production of the electric light, the currents may be transmitted to the carbon points in alternate directions, as they are produced. For electro-metallurgical purposes they are brought into one constant direction by a commutator, as in Clarke's machine above described. The driving-power required for lighthouse purposes is about three horse-power.

Machines of this class are never constructed now, as the same power is obtained with only a fifth of the weight in the machines of Siemens and Gramme.

823. Siemens' Armature.—An important improvement in Clarke's machine was introduced by Siemens of Berlin in 1854. It consists

in the adoption of a peculiar form of electro-magnet, which is represented in Fig. 545. The iron portion is a cylinder with a very deep and wide groove cut along a pair of opposite sides, and continued round the ends. The coil is wound in this groove like thread upon a shuttle. Regarded as an electro-magnet, the poles are not the ends of the cylinder, but are the two cylindrical faces which have not been cut away. In Fig. 546, *a b* is a section of the armature with the coil wound upon it. A B M N is a socket within which the armature revolves, the portions A B being of iron, and M N of brass.

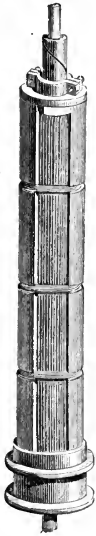


Fig. 545. Siemens' Armature.

The advantage of Siemens' armature is that, on account of the small space required for its rotation, it can be kept in a region of very intense magnetic force by the use of comparatively small magnets. Its form is also eminently favourable to rapid rotation. It is placed between the opposite poles of a row of horse-shoe magnets which bestride it along the whole of its length, as shown at the top of Fig. 548, and is rotated by means of a driving-band passing over the pulley shown at the lower end of Fig. 545.

The polarity of the electro-magnet is reversed at each half-revolution as in Clarke's arrangement, and the alternately opposite currents generated are reduced to a common direction by a commutator nearly identical with Clarke's, and represented in Figs. 545, 547. Siemens' machines are much more powerful than Clarke's when of the same size.

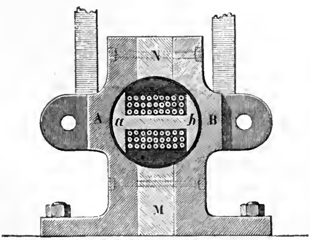


Fig. 546.—Section of Siemens' Armature.

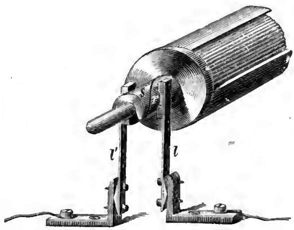


Fig. 547.—Commutator.

824. Accumulation by Successive Action: Wilde's Machine.—By

employing the current from a Siemens' machine to magnetize soft iron, we can obtain an electro-magnet of much greater power than the steel magnets from whose induction the current was derived. By causing a second coil to rotate between the poles of this electro-

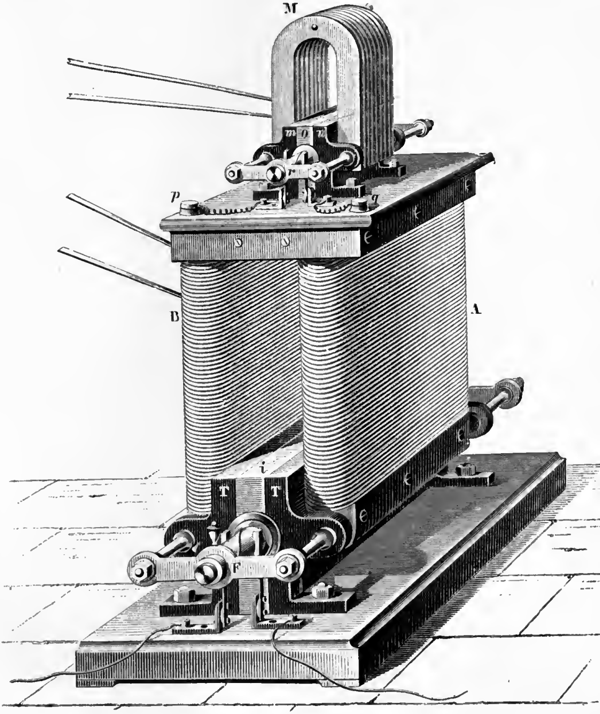


Fig. 548.—Wilde's Machine.

magnet, we can cbtain a current of much greater power than the primary current. This is the principle of Wilde's machine, which is represented in Fig. 548. It consists of two Siemens' machines, one above the other. The upper machine derives its inductive action from a row of steel magnets M, whose poles rest on the soft-iron masses m, n, forming the sides of the socket within which a Siemens'

armature r rotates. The currents generated in the coil, after being reduced to a uniform direction by a commutator, flow to the binding-screws p, q. These are the terminals of the coil of the large electro-magnet A B, through which accordingly the current circulates. The core of this electro-magnet consists of two large plates of iron, connected above by another iron plate, which supports the primary machine. Its lower extremities rest, like those of the primary magnets, on two iron masses T, T, separated by a mass of brass i; and a second Siemens' armature F, of large size, revolving within this system, furnishes the currents which are utilized externally.

Wilde's machine produces calorific and luminous effects of remarkable intensity; but the speed of rotation required is very great, being sometimes 1500 revolutions a minute for the large, and 2000 for the small armature. This great speed involves serious inconveniences; and the machine does not appear to have been used for lighthouses, or other practical purposes.

Wilde's principle can be carried further. The current of the second armature can be employed to animate a second electro-magnet of greater power than the first, with a third Siemens' armature revolving between its poles. This has actually been done by Wilde. By means of the current from this triple machine, driven by 15 horse-power, a bar of platinum 2 feet long and a quarter of an inch in diameter was quickly melted. This system of accumulation could probably be carried several steps further if desired.

825. Accumulation by Mutual Action; Dynamo-electric Machines.—Siemens and Wheatstone nearly simultaneously proposed the construction of a magneto-electric machine in which the induced currents are made to circulate round the soft-iron magnet which produced them. Iron has usually some traces of permanent magnetism, especially if it has once been strongly magnetized. This magnetism serves to induce very feeble currents in a revolving armature. These currents are sent round the iron magnet, thus increasing its magnetization. This again produces a proportionate increase in the induced currents; and thus, by a successive alternation of mutual actions, very intense magnetization and very powerful currents are speedily obtained. Machines constructed on this principle are called *dynamo-electric*. In the machine as exhibited by Siemens in 1867, the current was diverted into an external circuit, at regular intervals, by an automatic arrangement.

826. Ladd's Machine.—Ladd in 1867 constructed a dynamo-electric

machine having two revolving armatures, one for augmenting and sustaining the power of the electro-magnet, and the other for giving an external current.

B, B′ (Fig. 549) are two plates of iron surrounded by coils which are connected together at the right-hand end. The other ends are attached to two binding-screws connected with the ends of the coil of a Siemens' armature a'. The direction of winding of the two large coils B B′ is the same as for a horse-shoe magnet, so that

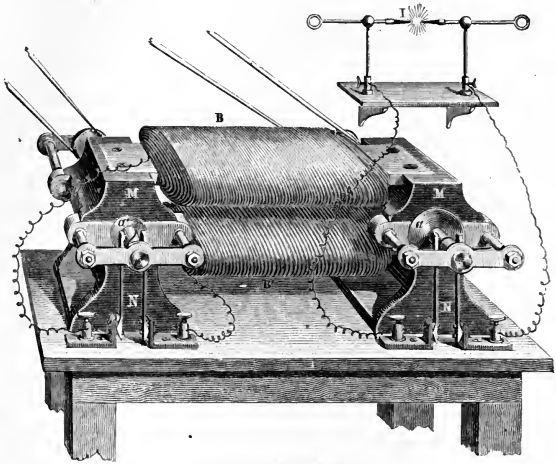


Fig. 549.—Ladd's Machine.

the two poles at either end are of opposite sign. The ends of the cores are let into masses of soft iron M M, N N, between which two armatures $a\,a'$ rotate. The coil of the armature a is connected with the external circuit containing, for example, two carbon points for exhibiting the electric light.

On the principle of mutual action, the electro-magnets B, B′, which we may suppose to have at first only a trace of magnetism, are soon raised to very intense magnetization by the rapid rotation of the armature a', and as long as the rotation continues, the magnetization is maintained. The rapid rotation of the other armature a between the poles thus strongly excited, produces a very powerful current which can be utilized externally.

Ruhmkorff modified this arrangement by employing a single rotating armature with two coils wound upon it, one of them being connected with the electro-magnet, and the other with the external circuit.

827. Siemens' Machine.—Siemens' dynamo-electric machine, as now constructed, is shown in Figs. 550, 551.

The armature consists of a hollow iron cylinder, on the outside of which the wire is wound lengthwise in from ten to twenty succes-

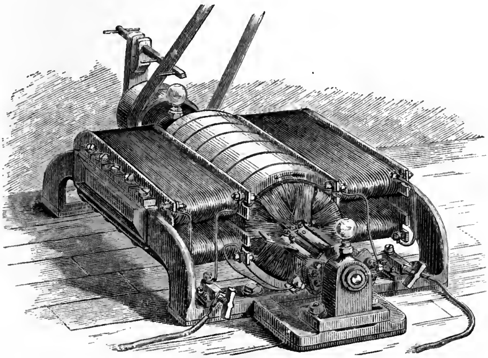


Fig. 550.—Siemens' Dynamo-electric Machine.

sive sections, each section being wound in the same manner as the whole coil of the original Siemens' armature (Fig. 545), and being like it connected at its ends to two opposite segments of a commutator, as well as to one end of each of the two adjacent sections; so that the whole wire forms one continuous coil, connected at a number of equidistant points with the successive segments of a commutator. The commutator is on the same plan as that of Clarke (Fig. 543), but instead of only two segments has a considerable number. Two contact springs or flexible bundles of wire called brushes rub upon the commutator at two points fixed in space, as it revolves, one of them receiving from the armature positive and the other negative electricity. The armature is rapidly rotated between two sets of curved iron bars, one set above the armature, as shown in Fig. 550, and the other, precisely similar set below. These

bars are prolonged at both ends through the four fixed coils shown in Figs. 550, 551, so that the upper bars, for example, form the core of the two upper fixed coils. The currents in these two coils are in opposite directions, so that the bar has a "consequent point" in the middle of its length. If these middle points are north poles, then the middle points of the lower bars are south poles, and each section of the coil by revolving between these two poles has currents generated in it which are reversed twice in each revolution, namely, in the two positions (differing by 180°) in which the maximum number of tubes of force pass through it. The two segments of the commutator which are in direct connection with the section in question make contact with the collecting brushes midway between these two reversals; and the current given off is due partly to this section and partly to the neighbouring sections on each side of it.

The fixed magnets are called the *field-magnets*, because their function is to produce a strong magnetic field for the armature to move in. Their coils are of stout wire, and the connections are usually

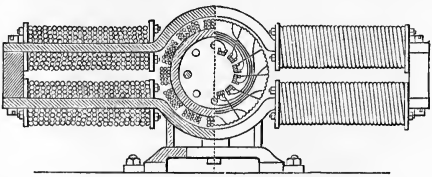


Fig. 551.—Section of Siemens' Machine.

such that the whole current generated in the armature passes through them; the armature coils, the field-magnet coils, and the external circuit being joined in series. Sometimes, however, the field-magnet coils are arranged in parallel circuit with the external resistance, so as only to receive a portion of the whole current.

828. Gramme's Machine.—Another well-known type of magneto-electric machine is that invented by M. Gramme, the construction of which is peculiar. Let C D E F (Fig. 552) be a ring of soft iron, wrapped round with insulated copper wire, and revolving in its own plane between the poles P, P′ of a fixed magnet. The ring will, at any given instant, consist virtually of two semicircular magnets, F C D, F E D, having a pair of similar poles at F, and the other pair at D, these being the points directly opposite the poles of the fixed

magnet. Since the poles of the ring remain fixed in space, the electric effect in the copper wire is the same as if the wire coil alone rotated, its core remaining stationary. The effect of this rotation would be, that in the portion C F E of the coil there would be electro-motive force tending to produce a current in one direction,—say the direction C F E; while in the other half, C D E, there would be electro-motive force tending to produce a current in the opposite direction—that is the direction C D E. The effects in the two halves are opposite as regards the current which they tend to produce in the coil as a whole; but they are the same as regards the electro-motive force between the opposite points C and E; and if the two ends of an external conductor be maintained in rubbing contact with the coil at these two points, a permanent current will flow through it in virtue of this electro-motive force.

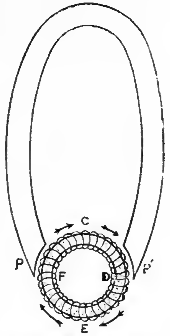


Fig. 552.—Magnet and Ring.

The above reasoning may be put in the following form. Nearly all the tubes of force which run from one pole to the other of the permanent magnet are concentrated in the substance of the iron ring, one half traversing the upper and the other the lower half-ring. Each convolution of the coil, in ascending from its lowest position E by way of F to its highest position C, cuts each of these tubes once, and all in the same direction, namely, from below to above. In descending on the other side by way of D to E, the same tubes are cut, each once, in the opposite direction, namely, from above to below. Hence the movement in E F C generates electro-motive force in one direction through the wire composing the coil, and the movement in C D E generates electro-motive force in the opposite direction; both parts of the motion conspiring to produce difference of potential between the convolution at C and that at E.

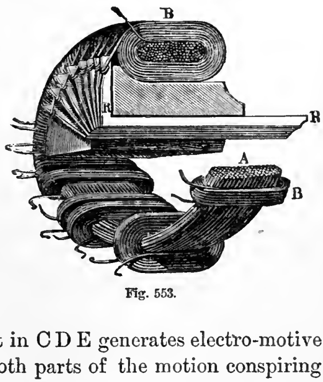


Fig. 553.

The details of the armature of Gramme's machine are shown in Fig. 553, in which different parts are represented in different stages of construction.

The ring or core consists of a bundle of iron wires, shown in section at A. The copper wire, covered as usual with an insulating material, is divided into a number of separate coils, as B B. The two ends of each coil are respectively connected to two thick pieces of copper (one of which is marked R R in the figure), which are the segments of the commutator, their number being equal to the number of separate coils. In passing the two points most remote from the poles, these coppers rub against two brushes, connected respectively with two binding-screws, one forming the positive and the other the negative electrode of the machine. As each brush makes contact with two or more coppers at the same time, the current is never interrupted, and undergoes but small fluctuations of strength, —a remark which also applies to Siemens' machine.

In consequence of the great steadiness of the current thus obtained,

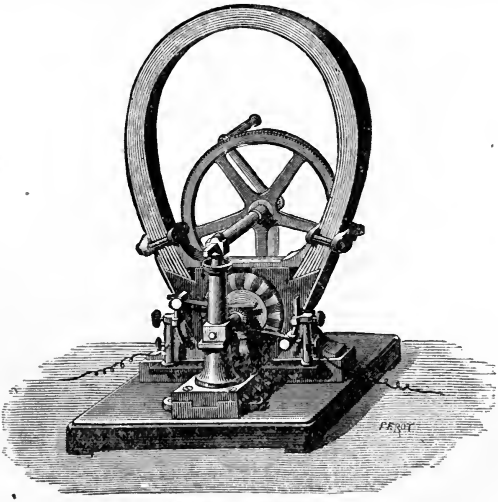


Fig. 554.—Gramme's Magneto-electric Machine, for hand-power.

such machines can be used instead of galvanic batteries for nearly all purposes. The machine as constructed for hand use is shown in

Fig. 554. Fig. 555 represents a larger pattern, intended to be driven by steam power. The armature revolves between the poles of four very powerful electro-magnets actuated by the current which the machine produces. The two upper magnets may be regarded as forming one magnet, with a consequent point in the centre, directly above the armature; and the two lower magnets give, in like manner, a consequent point, opposite in name to the former, directly below the armature.

The first machine with a ring like that of Gramme was a small laboratory model constructed by Pacinotti at Pisa in 1860, and described by him in an Italian publication in 1864, but it did not become generally known, nor was any large machine of the kind

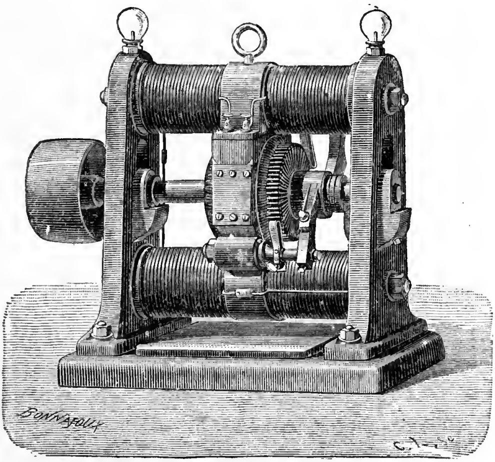


Fig. 555.—Gramme's Dynamo-electric Machine, for steam-power.

made, till the reinvention of the ring by Gramme, who was the first to introduce the now usual arrangement of collecting currents by flexible bundles of wire rubbing on a commutator of many segments.

Such machines as those of Gramme and Siemens above described are called *direct-current machines*, because the current which they send through the external circuit is always in the same direction.

They are also called *continuous-current machines,* because this current is never interrupted. All such machines can be used as electro-motors, that is to say, they can be driven by sending a current through them from an external source; and if we want to drive them forwards we must send this current in the backward direction; for (§ 804) the current generated by the machine, or a current in the same direction as this derived from an external source, tends to stop the machine and turn it backwards.

Another important class of machines produce *alternating* currents, that is to say, currents whose direction is alternately in one direction and the opposite, the reversals succeeding each other usually some hundreds or thousands of times in a second. For this purpose no commutator is required, inasmuch as the current in the armature itself is alternating in all machines; but the two collecting springs rub without interruption on the surfaces of two revolving cylinders, to which the ends of the armature-coil or of its several sections are connected. Each cylinder gives off positive and negative electricity alternately, and when the one is giving off positive the other is giving off negative. This is the favourite plan for light-houses, because the alternating currents make the two carbons of the electric lamp burn away equally, and thus facilitate the keeping of the light in the focus of the optical apparatus. The field-magnets of an alternate-current machine, if they are electro-magnets, must be excited by a current distinct from that of the machine itself; as alternating currents will not serve for this purpose.

829. Wheatstone's Telegraphic Currents.—In Wheatstone's Universal Telegraph (more fully described in § 841) the magneto-electric currents which give the signals are produced by causing a small flat bar of soft iron to rotate rapidly before the poles of a steel horse-shoe magnet, which has two connected coils of wire wound upon it in the same manner as upon electro-magnets. It is in these coils that the currents are generated, the iron bar being a temporary magnet, and thus influencing the coils, nearly in the same manner as if it were a permanent magnet. A current is induced in one direction as it approaches the poles, and in the opposite direction as it recedes from them, so that altogether four currents are generated in each complete revolution. On account of the lightness of the bar, it can be rotated with great rapidity.

830. Arago's Rotations.—Faraday successfully applied his discovery of magneto-electric induction to account for a phenomenon

first observed by Arago in 1824, and subsequently investigated by Babbage and Sir John Herschel. A horizontal disc of copper *b b* (Fig. 556), placed in the interior of a box, is set in rapid rotation by turning a handle. Just over the copper disc, but above the thin glass plate which forms the top of the box, a magnetized needle *a a* is balanced horizontally. When the disc is made to rotate, the needle is observed to deviate from the meridian in the direction of the rotation. When the speed of rotation exceeds a certain limit, the needle is not only deflected, but carried round in continuous rotation in the same direction as the disc.

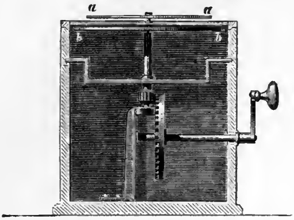


Fig. 556.—Arago's Rotations.

The explanation is to be found in the currents which are induced in the disc by its motion in the vicinity of the magnetized needle. The forces between these currents and the needle are (by Lenz's law) such as to urge the disc backwards; and, from the universal relation which subsists between action and reaction, they must be such as to urge the needle forwards, hence the motion. The direction of the induced current through the centre of the disc at any instant is along that diameter which is directly under the needle, the circuit being completed through the lateral portions of the disc; and it is evident that a current thus flowing parallel to the needle underneath it tends to produce deflection. If the continuity of the disc is interrupted by radial slits, the observed effect is considerably weakened inasmuch as the return circuit is broken. Faraday succeeded in directly demonstrating the existence of currents in a disc rotating near a fixed magnet, by exploring its surface with the amalgamated ends of two wires connected with a galvanometer.

The experiment performed by Arago may be reversed by setting the magnet in rotation, and observing the effect produced on the disc. The latter, if delicately suspended, will be found to rotate in the same direction as the magnet. This experiment was first performed by Babbage and Herschel. Its explanation is identical with that just given. In both cases the induced rotation must be slower than that of the body turned by hand, as the existence of the induced currents depends upon the motion of the one body relative to the other.

When an iron disc is used instead of a copper one, magnetism is induced in the portions which pass under the poles of the magnet; and as this requires a sensible time for its disappearance, there is always attraction between the poles of the needle and the portions of the disc which have just moved past. The needle is thus drawn forwards by magnetic attraction, and the observed effect is similar to that obtained with the copper disc, though the cause[1] is altogether different.

831. Copper Dampers.—Precisely similar to the above is the explanation of the utility of a copper disc in checking the vibrations of a magnetized needle under which it is fixed. As the needle swings to either side, its motion induces currents in the copper which urge the needle in the opposite direction to that in which it is moving. When it rests for an instant at the extremity of its swing, the currents cease; and as soon as it begins to return, the currents again resist its motion. A copper plate thus used is called a *damper*, and the vibrations thus resisted and destroyed are said to be *damped.* The name is applied to any other means for gradually destroying vibrations.

The resistance which induced currents oppose to the motion producing them is well illustrated by Faraday's experiment of the *copper cube.* A cube of copper is suspended by a thread, and set spinning by twisting the thread and then allowing it to untwist. If, while spinning, it is held between the poles of a powerful magnet, like that represented in Fig. 445, it is instantly brought almost to rest. If the poles are brought very near together, so as to heighten the intensity of the field, and a thin sheet of copper is inserted between them and moved rapidly in its own plane, the operator feels its motion resisted by some invisible influence. The sensation has been compared to that of cutting cheese. Foucault's apparatus for the heating of a copper disc by rotating it between the poles of a magnet (§ 486), is another illustration of the same principle. In all cases where induced currents are generated, and are not called upon to perform external work, they yield their full equivalent of heat.

The advantage of employing copper in experiments of this kind arises from its superior conductivity, to which the induced currents are proportional.

[1] That is to say, the *main cause;* for there must be induced currents in the iron as well as in the copper, though inferior in strength, on account of the inferior conductivity of the former metal.

832. Electro-medical Machines.—The application of electricity is often resorted to for certain nervous affections and local paralyses. Many different forms of apparatus are employed for this purpose. One of the most convenient is represented in Fig. 557. Two small coils connected with each other, and furnished with a vibrating contact-breaker, are traversed by the current from a miniature battery. The coils are surrounded by hollow cylinders of copper or brass, in which induced currents are generated as often as the current in the coils is established or interrupted. This action diminishes the energy of the extra-currents on which the shock depends, and the operator can accordingly regulate its strength at pleasure by sliding the cylinders on or off.

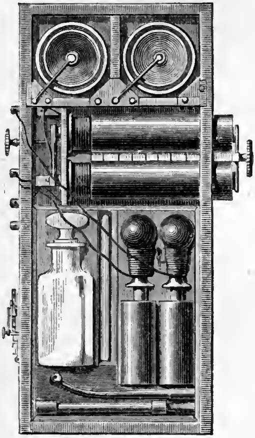


Fig. 557.—Electro-medical Machine.

833. Caution regarding Lines of Force.—After the very extensive use which has been made in this chapter of lines and tubes of force, we think it right to caution the reader against supposing that these conceptions depend upon any doubtful hypothesis. They merely serve, like meridians and parallels of latitude, to map out space in a mode convenient for the statement of physical laws.

CHAPTER LX.

ELECTRIC TELEGRAPHS.

834. Electric Telegraph: History.—The discovery that electricity could be transmitted instantaneously to great distances, at once suggested the idea of employing it for signalling. Bishop Watson, already referred to in § 636, performed several experiments of this kind in the neighbourhood of London, the most remarkable being the transmission of the discharge of a Leyden-jar through 10,600 feet of wire suspended between wooden poles at Shooter's Hill. This was in 1747. A plan for an alphabetical telegraph to be worked by electricity is minutely described in the *Scots Magazine* for 1753, but appears to have been never experimentally realized. Lesage, in 1774, erected at Geneva a telegraph line, consisting of twenty-four wires connected with the same number of pith-ball electroscopes, each representing a letter. Reusser, in Germany, proposed, in the same year, to replace the electroscopes by spangled panes exhibiting the letters themselves. The difficulty of managing frictional electricity was, however, sufficient to prevent these and other schemes founded on its employment from yielding any useful results. Volta's discoveries, by supplying electricity of a kind more easily retained on the conducting wires, afforded much greater facilities for transmitting signals to a distance.

Several suggestions were made for receiving-apparatus to exhibit the effects of the currents transmitted from a voltaic battery. Sömmering of Munich in 1811 proposed a telegraph, in which the signals were given by the decomposition of water in thirty-five vessels, each connected with a separate telegraph wire. Ampère, in 1820, proposed to utilize Œrsted's discovery, by employing twenty-four needles, to be deflected by currents sent through the same

number of wires; and Baron Schilling exhibited in Russia, in 1832, a telegraphic model in which the signals appear to have been given by the deflections of a single needle.[1]

Weber and Gauss carried out this plan in 1833, by leading two wires from the observatory of Göttingen to the Physical Cabinet, a distance of about 9000 feet. The signals consisted in small deflections of a bar-magnet, suspended horizontally with a mirror attached, on the plan since adopted in Thomson's mirror galvanometer.

At their request the subject was earnestly taken up by Professor Steinheil of Munich, whose inventions contributed more perhaps than those of any other single individual to render electric telegraphs commercially practicable. He was the first to ascertain that earth-connections might be made to supersede the use of a return wire. He also invented a convenient telegraphic alphabet, in which, as in most of the codes since employed, the different letters of the alphabet are represented by different combinations of two elementary signals. Two needles were employed, one or the other of which was deflected according as a positive or a negative current was sent, the deflections being always to the same side. Sometimes the needles were merely observed by eye, sometimes they were made to strike two bells, and sometimes to produce dots, by means of capillary tubes charged with ink, on an advancing strip of paper, thus leaving a permanent record on the strip in the shape of two rows of dots. His currents were magneto-electric, like those of Weber and Gauss.

The attraction of an electro-magnet on a movable armature fur-

[1] The contributions of Mr. (now Sir Francis) Ronalds to the art of telegraphy must not be altogether overlooked. According to an able notice in *Nature*, Nov. 23, 1871, "Sir Francis, before 1823, sent intelligible messages through more than eight miles of wire insulated and suspended in the air. His elementary signal was the divergence of the pith-balls of a Canton's electrometer produced by the communication of a statical charge to the wire. He used synchronous rotation of lettered dials at each end of the line, and charged the wire at the sending end whenever the letter to be indicated passed an opening provided in a cover; the electrometer at the far end then diverged, and thus informed the receiver of the message which letter was designated by the sender. The dials never stopped, and any slight want of synchronism was corrected by moving the cover. Hughes' printing instrument is the fully-developed form of this rudimentary instrument. A gas pistol was used to draw attention, just as now a bell is rung. The primary idea of reverse currents is to be found where Sir Francis suggests that the wire when charged with positive electricity should discharge not to earth but into a battery negatively charged. Equally interesting is the discussion on what we now call lateral induction, then known as compensation. The author clearly saw that in the underground wires which he suggests as substitutes for aerial lines, this induction would be or might be a cause of retardation."

nishes another means of signalling. This was the foundation of Morse's telegraphic system, and was employed by Wheatstone for ringing a bell to call attention before transmitting a message.

About the year 1837 electric telegraphs were first established as commercial speculations in three different countries. Steinheil's system was carried out at Munich, Morse's in America, and Wheatstone and Cooke's in England. The first telegraphs ever constructed for commercial use were laid down by Wheatstone and Cooke, on the London and Birmingham and Great Western Railways. The wires, which were buried in the earth, were five in number, each acting on a separate needle; but the expensiveness of this plan soon led to its being given up. The single-needle and double-needle telegraphs of the same inventors have been much more extensively used, the former requiring only one wire, and the latter two.

Wheatstone made several subsequent contributions to the art of telegraphy, some of which we shall have occasion to mention in later sections.

835. Batteries.—All the public telegraphs in this country have now for many years been worked by voltaic currents; the magneto-electric system, which was tried on some lines, having been found to involve a needless expenditure of labour.

The modified Daniell's which was described in our earlier editions has been largely replaced by a bichromate battery of greater electromotive force and much less resistance. The outer portion of each cell contains a small cylinder of carbon immersed in a solution of bichromate of potash in dilute sulphuric acid. In the centre is a porous jar containing a zinc cylinder immersed partly in mercury and partly in dilute sulphuric acid, the mercury being at the bottom and the acid above. This arrangement keeps the zinc constantly amalgamated.

836. Wires.—The wires for land telegraphs are commonly of what is called galvanized iron, that is, iron coated with zinc, supported on posts by means of glass or porcelain insulators, so contrived that some part of the porcelain surface is sheltered from rain, and insulates the wires from the posts even in wet weather. Wires thus suspended are called *air-lines.*

Underground wires are, however, sometimes employed. They are insulated by a coating of gutta percha, and are usually laid in pipes, an arrangement which admits of their being repaired or renewed without opening the ground except at the drawing-in

boxes. There is less leakage of electricity from subterranean than from air lines, but their cost is greater, and they are less suited for rapid signalling, on account of the retardation caused by the inductive action between the wire and the conducting earth, which is similar to that between the two coatings of a Leyden-jar.

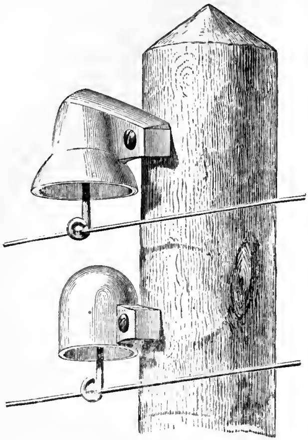


Fig. 558.—Insulators.

The early inventors of electric telegraphs supposed that a current could not be sent from one station to another without a return wire to complete the circuit. Steinheil, while conducting experiments on a railway, with the view of ascertaining whether the rails could be employed as lines of telegraph, made the discovery that the earth would serve instead of a return wire, and with the advantage of diminished resistance; the earth, in fact, behaving like a return wire of infinitely great cross-section, and therefore of no resistance.

We are not, however, to suppose that the current really returns from the receiving to the transmitting station through the earth. The duty actually performed by the earth consists in draining off the opposite electricities which would otherwise accumulate in the terminals. It keeps the two terminals at the same potential; and as long as this condition is fulfilled, the current will have the same strength as if the terminals were in actual contact.

837. Single-needle Telegraph.—One of the best known telegraphs in this country, though little or not at all employed elsewhere, is the single-needle instrument of Wheatstone and Cooke, represented in Figs. 559, 560, the former showing its external appearance, and the latter its internal arrangements as seen from behind. The needle, which is visible in front, is one of an astatic pair, its fellow being in the centre of the coil C C. When the handle H hangs straight down, the instrument is in the position for receiving signals from another station. The current from the line-wire enters at L, and, after traversing the coil and deflecting the needle, escapes

through the earth-wire E, having taken in its course the two tall contact-springs t' t.

To send a current to another station, the handle H is moved to one side, and the current sent will be positive or negative according to the side to which the handle is moved. The handle turns the

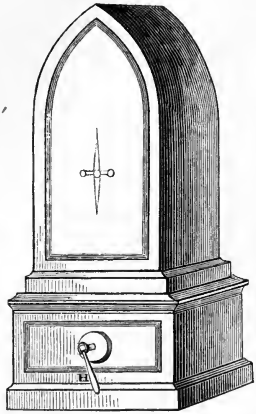


Fig. 559.—Single-needle Instrument.

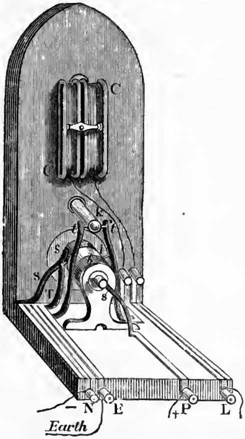


Fig. 560.—Internal Arrangements.

cylindrical arbor a b, which is divided electrically into two parts by an insulator in the middle of its length. Each of these parts has a pin projecting from it, one pin being above, and the other below. These are vertical when the handle is vertical, and are then doing no duty; but when the handle is put to one side, the upper pin (which is attached to b) makes contact with one of the tall springs t t', at the same time pushing it away from the metallic rest k, and thus putting it out of connection with the other tall spring; while the lower pin (which is attached to a) makes contact with one of two short springs T T′, only one of which is shown in the figure. There is permanent connection between a and the negative pole of the battery through the spring s, and between b and the positive pole through the spring s'. In the position represented in the figure, a serves to connect the negative pole of the battery with the earth, and b serves to connect the positive pole with the spring t', down

which the current passes from the point of contact of the pin, and then through the coil to the line-wire at L. The needle of the sending station is thus deflected to the same side as that of the receiving station.

If the handle were moved to the other side, b would serve to connect the positive pole with the earth, and a would establish connection between the negative pole and the coil, which is itself connected with the line-wire.

Since the telegraphs of this country came into the hands of the Post-office, the alphabet devised by Wheatstone and Cooke has been given up, and the Morse alphabet (§ 842) adopted in its place. In the Morse alphabet, which is now the telegraphic alphabet of all nations, the shortest signs are allotted to those letters which occur most frequently. This was not the case with the old needle-alphabet, which was rather planned with the view of assisting the memory; and experience has shown that such assistance is quite unnecessary. The needle instrument has also, to a great extent, been superseded by Morse's instrument.

838. Dial Telegraphs.—Telegraphs in which the ordinary letters of the alphabet are ranged round the circumference of a dial, and are pointed at by a revolving hand, are specially convenient for those who are not professional telegraphists. They are constructed on the principle of step-by-step motion, the hand being advanced by successive steps, each representing one current sent or stopped.

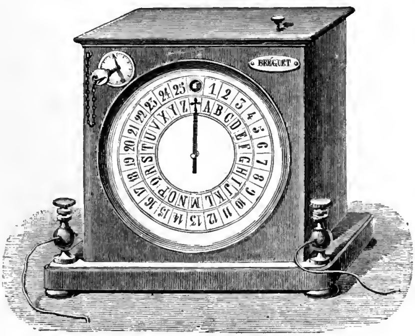


Fig. 561.—Breguet's Indicator.

One of the simplest instruments of this class is Breguet's, which is extensively used on the French railways. Fig. 561 represents the exterior of the receiving instrument. The dial is inscribed with the 25 letters of the French alphabet and a cross, making 26 signals in all. The hand (as in other step-by-step telegraphs) advances only in one direction, which is the same as that of the hands of a clock,

stopping before each letter which is to be indicated, and pointing to the cross at the end of each word. Fig. 562 shows the mechanism by which the motion is produced. A is the armature of an electro-magnet, the magnet itself being removed in the figure, to allow the other parts to be better seen. The two dotted circles traced on the armature represent vertical sections of the two coils, which rest on the bottom of the box, and have their axes horizontal. If introduced, they would nearly conceal the armature from view. The armature turns about a horizontal axis VV′, and is attached to an opposing

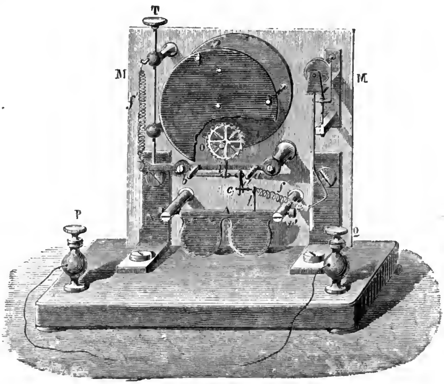


Fig. 562.—Mechanism of Indicator.

spring which draws it back from the magnet. The tension of this spring can be regulated by means of a lever acted on by a key outside the box. When a current is sent, the armature is attracted to the magnet; when the current ceases, the spring draws it back; and it thus moves continually to and fro during the transmission of a message. An upright arm l is attached to the armature, and carries a horizontal arm c, which lies between the two prongs of a fork d, represented on a larger scale in Fig. 563. This fork vibrates about a horizontal axis $a\,b$, to which is attached the vertical pallet i. This pallet acts upon an escapement wheel O, toothed in a peculiar way, the thickness of the teeth being only half the thickness of the wheel, and the teeth on one half of the thickness being opposite the spaces on the other half. The total number of teeth is 26, thirteen on each half of the thickness.

When no current is passing, the pallet i is engaged with one of the teeth on the remote side, as represented in Fig. 563. When a current passes, the armature is attracted, and the pallet is moved over to the near side, thus releasing the tooth with which it was previously engaged, and becoming engaged with the next tooth on the near side of the wheel. The wheel, which is urged by a clock-movement, thus advances $\frac{1}{26}$ of a revolution; and the hand on the dial, being attached to the wheel, moves forward one letter. When the current ceases, the pallet moves back to the remote side, and the hand is advanced another letter. If the hand is initially at the cross, it will be advanced to any required letter by so arranging matters that the number of currents *plus* the number of interruptions shall be equal to the number denoting the place of the letter in the alphabet. To effect this arrangement is the office of the sending instrument.

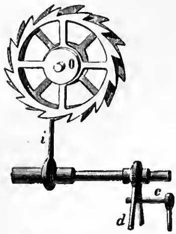


Fig. 563.—Escapement.

839. Sending Instrument.—This is represented in Fig. 564. There is a dial inscribed with 25 letters and a cross, like that of the receiving instrument, and an arm which can be carried round the dial by a handle M. There are 26 notches cut in the edge of the dial, in which a pin attached to the movable arm catches; and the arm is allowed sufficient play to and from the face of the dial to admit of this pin being easily released or inserted. When the pin is in one of the notches, the instrument is in position for transmitting the corresponding letter. The action is as follows:—

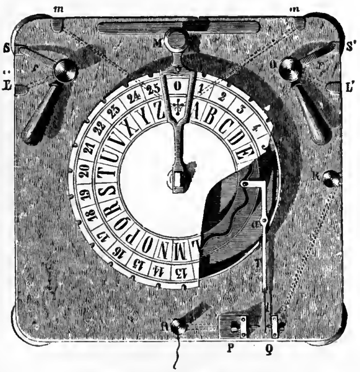


Fig. 564.—Breguet's Manipulator.

A toothed or rather undulated wheel is fixed on the same axis as the revolving arm, and turns with it. There are 13 projections and 13 hollows on its circumference, a few of which are shown in the

figure where the face is cut away. A bent lever T, movable about an axis at a, bears at one end against the circumference of the undulated wheel, while its other end plays between two points P, Q, and is in contact with one or other of these points whenever its upper end bears against a hollow or a projection. P is in connection with a battery, and Q with the earth, the undulated wheel being in connection with the line-wire. The movement of the handle thus produces the requisite number of currents and interruptions.

840. Alarum.—Besides the sending and receiving apparatus above described, each station has an *alarum*, which is employed to call attention before sending a despatch. There are several different kinds. Fig. 565 represents the *vibrating alarum*, which is one of the simplest. It contains an electro-magnet e, with an armature f fixed to the end of an elastic plate. When no current is passing through the coil, the armature is held back by the elasticity of this plate, so as to press against a contact-spring g connected with the binding-screw m. The terminals of the coil are at the binding-screws p, p', the former of which is in connection with the armature, and the latter with the earth. As long as the armature presses against the spring g, there is communication between the two binding-screws m and p' through the coil; but the passing of a current produces attraction of the armature, which draws it away from g and interrupts the current. The electro-magnet is thus demagnetized, and the armature springs back against g, so as to allow a fresh current to pass. The armature is thus kept in continual vibration; and a hammer K, which it carries above, produces repeated strokes on a bell T.

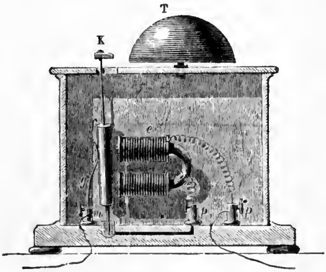


Fig. 565.—Vibrating Alarum.

841. Wheatstone's Universal Telegraph.—The first step-by-step telegraph was invented by Wheatstone; and the most perfect instrument of the class is probably his "Universal Telegraph," which is now in such general use in this country for connecting places of business. The currents employed are magneto-electric, and are alternately positive and negative. They produce successive reversals of

polarity in an electro-magnet, which acts upon a light steel magnet —a kind of astatic needle—and causes it to rotate through a large angle first in one direction, and then in the opposite. Each of these rotations causes a ratchet-wheel to advance one tooth, and this causes the pointer to advance one letter. At the same time the turning of the handle by which the currents are generated, causes the pointer of the sending instrument to advance one letter for each current sent, so that the pointers at the two stations indicate the same letter. The same dial which serves for sending, also serves for receiving. It is surrounded by a number of keys or buttons, one against each letter. When any letter is to be sent, its key is depressed, the operator continuing all the time to turn the handle for generating currents. Previous to putting down a key, these currents complete their circuit within the instrument; but when a key is down, every current generated travels along the line to the receiving station, until the pointers have been advanced step by step to the corresponding letter. As soon as this has been reached, the currents are again confined to the sending instrument; and the pointers will make no further advance till another key is put down.[1]

842. Morse's Telegraph.—Morse's apparatus, first tried in America about 1837, is now perhaps the most extensively used of all.

His receiving instrument, or *indicator*, in its primitive simplicity, consists (Fig. 566) of an electro-magnet, a lever movable about an axis, carrying a soft-iron armature at one end, and a pencil at the other, and a strip of paper which is drawn past the pencil by a pair of rollers.

As the pencil soon became blunt, and was uncertain in its marking, a point, which scratched the paper, was substituted. This has now to a great extent been superseded by an ink-writer, which requires the exertion of less force, and at the same time leaves a more visible trace.

Fig. 567 represents Morse's indicator as modified by Digney. A train of clock-work, not shown in the figure, drives one of a pair of rollers $n\,m$, which draw forward a strip of paper $p\,p$ forming part of a long roll K. The same train turns the printing-cylinder H, the surface of which is kept constantly charged with a thick greasy ink by rolling-contact with the ink-pad L. The arma-

[1] For the details of the mechanism, reference may be made to Wheatstone's Patent, No. 1239 year 1858. A condensed account will be found in *Sabine on the Electric Telegraph*, pp. 82–84.

ture B B′ of the electro-magnet A is mounted on an axis at C, and

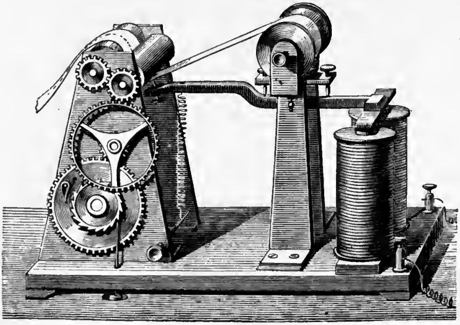


Fig. 566.—Morse's Telegraph.

carries a style at its extremity just beneath the printing-cylinder. When a current passes, the armature is attracted, and the style

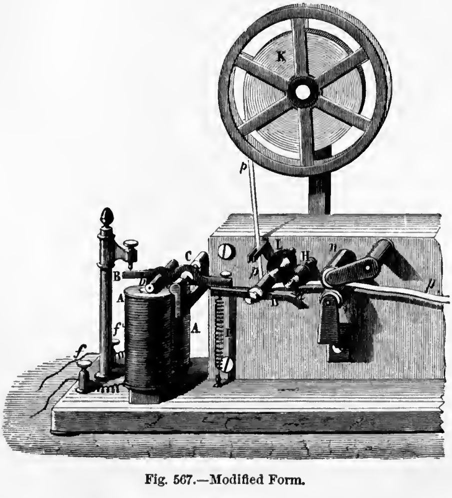


Fig. 567.—Modified Form.

presses the paper against the printing-cylinder, causing a line to be printed on it, the length of which depends on the duration of the

current, as the paper continues to advance without interruption. The lines actually employed are of two lengths, one being made as short as possible (-) and called a *dot*, the other being about three times as long (—) and called a *dash*. The opposing spring D restores the armature to its criginal position the moment the current ceases.

Morse's key (Fig. 568) is simply a brass lever, mounted on a hinge at A, and pressed up by the spring *f*. When the operator puts down the key, by pressing on the button K with his finger, the projections *c d* are brought into contact, and a current passes from the battery-wire P to the line-wire L. When the key is up, the projections *a b* are in contact, and currents arriving by the line-wire pass by the wire R to the indicator or the relay. By keeping the key down for a longer or shorter time, a dash or a dot is produced at the station to which the signal is sent. The dash and dot are combined in different ways to indicate the different letters, as shown in the following scheme, which is now generally adopted both in Europe and America:—

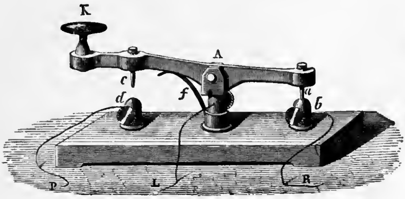


Fig. 568.—Morse's Key.

MORSE'S ALPHABET.

A - —	J - — — —	T —	1 - — — — —
Ä - — - —	K — - —	U - - —	2 - - — — —
B — - - -	L - — - -	Ü - - — —	3 - - - — —
C — - — -	M — —	V - - - —	4 - - - - —
D — - -	N — -	W - — —	5 - - - - -
E -	O — — —	X — - - —	6 — - - - -
É - - — - -	Ö — — — -	Y — - — —	7 — — - - -
F - - — -	P - — — -	Z — — - -	8 — — — - -
G — — -	Q — — - —	Ch — — — —	9 — — — — -
H - - - -	R - — -		0 — — — — —
I - -	S - - -	Understood - - - — -	

A space about equal to the length of a dash is left between two letters, and a space of about twice this length between two words.

In needle-telegraphs, the dot is represented by a deflection to the left, and the dash by a deflection to the right.

843. Relay.—Fig. 569 represents Morse's indicator in connection with what is called a *relay;* that is to say, an apparatus which, on receiving a feeble current from a distance, sends on a much stronger current from a battery on the spot. The key B being up, a current arriving by the line-wire passes through the key from *c* to *a*, thence

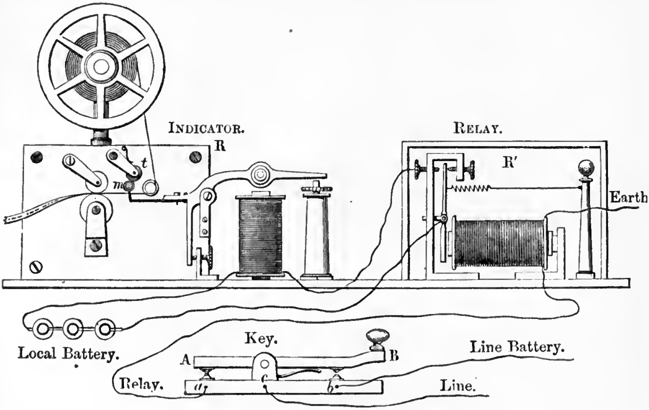


Fig. 569.—Morse's Apparatus, with Relay.

through another wire to the coil of the electro-magnet belonging to the relay, and through this coil to earth. The electro-magnet of the relay attracts an armature, the contact of which with the magnet completes the circuit of the local battery, in which circuit the coil belonging to the indicator is included. The armature of the indicator is thus compelled to follow the movements of the armature of the relay.

Relays are used when the currents which arrive are too much enfeebled to give clear indications by direct action. They are also frequently introduced at intermediate points in long lines which could not otherwise be worked through from end to end. The analogy of this use to change of horses on a long journey is the origin of the name. Relays are also frequently used in connection with alarums when these are large and powerful.

844. Hughes' Printing Telegraph.—The employment of Morse's alphabet requires on the average about three currents to be sent per letter. The extension of telegraphic service has stimulated the

industry of inventors to devise means for obtaining more rapid transmission. Hughes, about 1859, invented a system which requires only one current to be sent for each letter, and which, accordingly, sends messages in about a third of the time required by Morse's method. Hughes' machine also prints its messages in Roman characters on a strip of paper. These advantages are, however, obtained at the expense of extreme complexity in the apparatus employed. It is only fit for the use of skilled hands; but it is extensively employed on important lines of telegraph. We will proceed to indicate the fundamental arrangements of this marvellous piece of ingenuity.

Fig. 570 is a general view of the machine. It is propelled by powerful clock-work, with a driving-weight of about 120 lbs., and with a regulator consisting of a vibrating spring *l* acting upon a 'scape-wheel. A travelling weight on the spring can be moved towards either end to regulate the quickness of the vibrations. The clock-work drives three shafts or axes: (1.) the type-shaft, so called because it carries at its extremity the type-wheel T, which has the letters of the alphabet engraved in relief on its circumference at equal distances, except that a blank space occurs at one place instead of a letter; (2.) the printing-shaft, which turns much faster than the type-shaft, making sometimes 700 revolutions per minute, and carrying the fly-wheel V. These two axes are horizontal, and are separately represented in Fig. 571; (3.) a vertical shaft *a*, having the same velocity as the type-wheel, which drives it by means of bevel-wheels.

This vertical shaft consists of two metallic portions, insulated from each other by an ivory connecting-piece. In the position represented in Fig. 571, these two metallic parts are electrically connected by means of the screw V, but they will be disconnected by raising the movable piece *v*.

The revolving arm composed of the pieces *v′ v* is called the *chariot*. It revolves with the vertical shaft, and travels over a disc D pierced with as many holes as there are letters on the type-wheel, these holes being ranged in a circle round the base of the shaft, and at such a distance from the shaft that the extremity of the chariot passes exactly over them. In these holes are the upper ends of a set of pins *g*, which are raised by putting down a set of keys B N resembling those of a piano. When the chariot passes over a pin which is thus raised, the piece *v* is lifted away from *v′*, and the current from the battery, which previously passed from the pin through *v* and *v′*

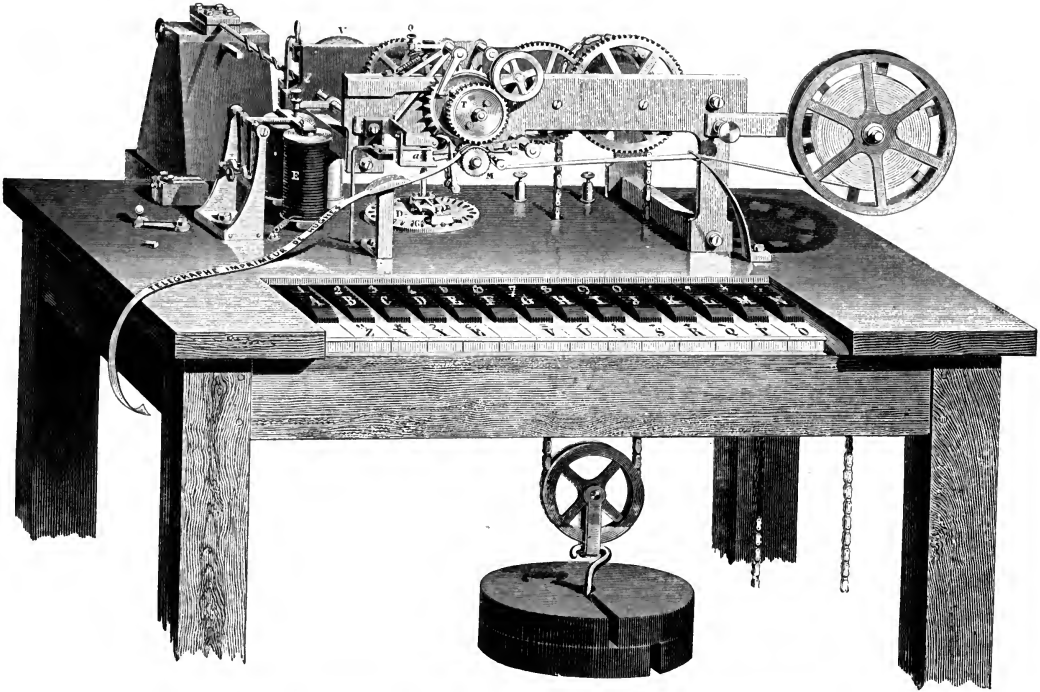


Fig. 570.—Hughes' Printing Telegraph.

to the earth, is now cut off from v', and passes through v to the electro-magnet, and thence to the line-wire.

This is the process for sending signals. We will now explain how a current thus sent causes a letter to be printed by the type wheels at both the sending and receiving stations, the sending and receiving instruments being precisely alike.

The current traverses the coils of an electro-magnet E (Fig. 570), beneath which is a permanent steel horse-shoe magnet, having its

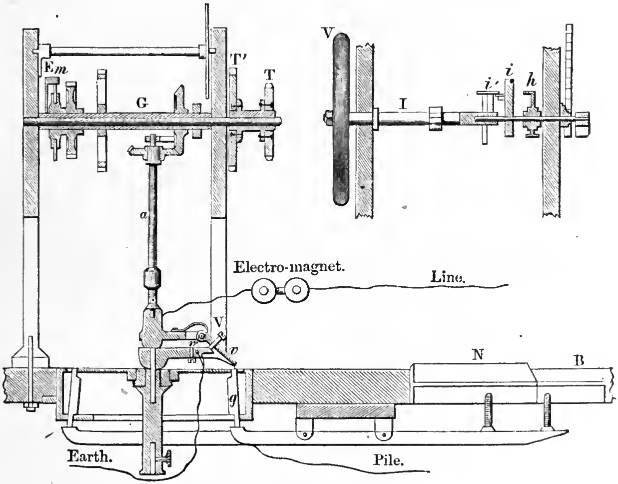


Fig. 571.—Type-shaft and Printing-shaft.

poles in contact with the soft-iron cores of the electro-magnet. When no current is passing, the influence of the steel renders these cores temporary magnets, and enables them to hold the movable armature p against the force of an opposing spring. The current is in such a direction that it tends to reverse the magnetism induced by the steel. It is not necessary, however, that it should be strong enough to produce an actual reversal, but merely that it should weaken the induced magnetism of the cores sufficiently to enable the opposing spring to overpower them. This is one of the most original parts of Hughes' apparatus, and is a main cause of its extreme sensibility.

The printing-shaft consists of two portions, one of which I (Fig. 571) carries the fly-wheel V, and turns uniformly under the action of the clock movement; the other, which is next the front of the machine, remains at rest when no current is passing; but when the armature of the magnet rises, the two parts of the shaft become locked together by means of the ratchet-wheel and click *i i′*.

The portion of the shaft which is thus turned every time a current passes, carries a very acute cam or tooth *p* (Fig. 572), which suddenly raises the lever *a b*, movable about an axis at one end T, and, by so doing, raises the paper against the type-wheel, and prints the letter. In order thus to print a letter from the rim of a wheel which continues turning, very rapid movement is necessary. This is secured by making the opposing spring which moves the armature very powerful, and the cam *p* very acute. The same movement of the lever which produces the impression, raises the arm J U, which carries a spring *r* with a click at its extremity. This click, in its ascent, glides over the teeth of the ratchet-wheel E; but locks into the teeth and turns the wheel in its descent, and by so doing, advances the paper through the distance corresponding to one letter. The spacing of the words is obtained by the help of the blank on the type-wheel.

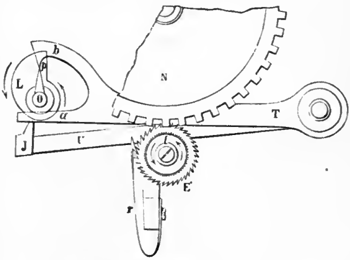


Fig. 572.—Mechanism for Printing.

The type-wheel should admit of easy adjustment to restore it to agreement with the chariot when accidental derangement may have occurred. For this purpose, the shaft G is made hollow, its internal and external portions being merely locked together by the click *m*, which is held in its place by a permanent current in either direction. On pressing down the button Q (Fig. 570), the click *m* is raised by the piece E, so as to leave the type-wheel free, and a pin is provided which catches in a notch corresponding to the blank on the type-wheel. The adjustment can also be made by hand.

Lastly, the shaft I carries a third cam, which, at each revolution of this axis, engages with a very coarse-toothed wheel T′, set on the same axis as the type-wheel, and pushes it a little forward or backward without detaching it from the driving gear. Small discrepan-

cies between the velocities of the type-wheel and chariot are thus corrected as often as a letter is printed. This contrivance serves to keep the receiving instrument from gaining or losing on the sending instrument during the transmission of a message. The type-wheel of the receiving instrument must be adjusted before the message begins, so as to make the two instruments start at the same letter.

845. Electro-chemical Telegraph.—Suppose a metallic cylinder, permanently connected with the earth, to be revolving, carrying with it on its surface a strip of paper freshly impregnated with cyanide of potassium. Also suppose a very light steel point permanently connected with the line-wire, and resting in contact with the paper. Every time that a current arrives by the line-wire, chemical action will take place at the point of contact, and the paper at this point will be discoloured by the formation of prussian blue. This is the principle of Bain's electro-chemical telegraph, which leaves a record in the shape of dots and dashes of prussian blue. The apparatus for sending signals is the same as in Morse's system. The paper must not be too wet, or the record will be blurred; neither must it be too dry, for then no record will be obtained.

846. Autographic Telegraph.—An autographic telegraph is one which produces at the receiving station a fac-simile of the original despatch. The best known instruments of this class are those of Bonelli and Caselli. We shall describe the latter.

At the sending station a sheet of metallized paper, with the despatch written upon it in a greasy kind of ink, is laid upon a cylindric surface M (Fig. 573). At the receiving station there is a

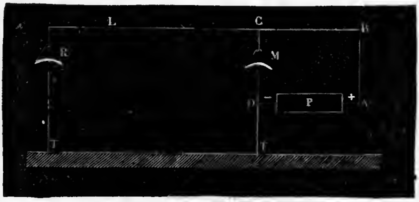


Fig. 573.—Principle of Caselli's Telegraph.

similar cylindric surface R, on which a sheet of Bain's chemical paper is laid. Two styles, driven by pendulums which oscillate with exact

synchronism, move over the surfaces of the two sheets, describing upon them very close parallel lines at a uniform distance apart, both styles being in permanent connection with the line-wire. The current is furnished by the battery P at the sending station. When the style is on a conducting portion of the paper M, the current takes

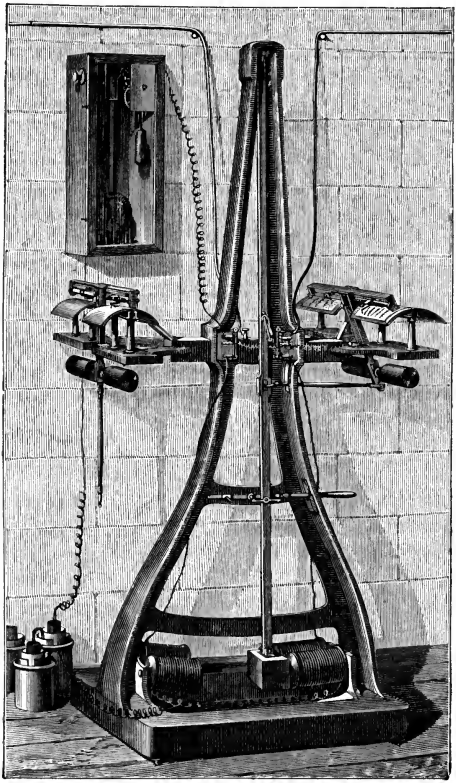


Fig. 574.—Caselli's Telegraph.

the course of least resistance A B C D, no sensible portion of it going to the other station. On the other hand, when the style is on the non-conducting ink in which the despatch is written, the circuit

ABCD is broken, and the current travels through the line-wire. At this moment the style on the sheet R is in exactly the same position as that on the sheet M, by reason of the synchronism of the pendulums, and a blue line will be produced which will be the exact reproduction of the broken line of the despatch traversed by the style. Accordingly, when the style of M has described a series of lines close together and covering the sheet, R will be covered with a series of points or lines forming a copy of the despatch. The tracing point is carried by a lever turning about an axis near its lower end. To this lower end is attached a connecting-rod, jointed at its other end to the pendulum (Fig. 574). While the pendulum swings in one direction, the style traces a line in one direction on the sheet. At the end of this stroke, an action occurs which, besides advancing the style, raises it, so that it does not touch the sheet during the return stroke.

The synchronism of the pendulums at the two stations, which is absolutely necessary for correct working, is obtained by means of two clocks which are separately regulated to a given rate, the clock-pendulums making two vibrations for one of the telegraphic pendulum. The bob of the latter consists of a mass of iron, and vibrates between two electro-magnets, which are made and unmade according to the position of the clock-pendulum, as the latter makes and breaks the circuit of a local battery. The mass of iron is thus alternately attracted by each of the two magnets as it comes near them, and is prevented from gaining or losing on the clock.

It is evident that the Caselli telegraph may be applied to copy not only letters but a design of any kind; hence the name of *pantelegraph* which has been given it. Fig. 575 represents a copy thus obtained upon Bain's paper. Fig. 576 represents a copy obtained at the same time upon a sheet of tin-foil, such as is usually placed beneath the paper. The current decomposes the moisture of the paper, and the hydrogen thus liberated reduces the oxide of tin, of which a small quantity is always present on the surface. If the foil be then treated with a mixture of nitric and pyrogallic acid, the traces are developed, and come out black.

The Caselli system has been used for some years on the telegraphs around Havre and Lyons, but has not realized the hopes of its promoters, its despatches being often illegible.

Instead of a series of parallel lines, the styles may be made to trace the successive convolutions of a fine helix, the two sheets being bent

round two cylinders, which revolve in equal times, and also advance longitudinally.

Fig. 575.—Fac-simile of Despatch.

Fig. 576.—Copy on Tin-foil.

847. Cowper's Writing Telegraph.—In the writing telegraph recently invented by Mr. Cowper, a pen at the receiving station imitates the movements of a pen at the sending station. Two wires are necessary, instead of only one as in other systems. One of these wires conveys a current which produces similarity of position as regards left and right displacement, while the other discharges the same function as regards up and down displacement. By the joint action of the two currents, when the sending pen is held in any part of the square field allotted to it, the receiving pen is brought to a similar position in its field of movement. Strips of paper are drawn past both pens by clockwork, and the writing upon one is imitated upon the other.

The mode of obtaining this conformity as regards either component of motion is as follows. The resistance in the circuit of the wire for left and right movement is altered by left or right movement of the sending pen, a number of resistance coils being so arranged that the current traverses a greater or less number of them according as the pen is nearer to one side of its square or the other. The current, on its arrival at the receiving station, traverses the coil of an electro-magnet, and thus deflects a needle, which, by means of a thread attached to one end, draws the pen aside, to a distance depending on the strength of the current.

848. Submarine Telegraphs.—The first submarine telegraph cable was laid between Dover and Calais in 1850; but, being insufficiently protected against the friction of the rocks, it only lasted a few hours The two Atlantic cables which were laid in 1866 appear to be still in perfect order.

Submarine cables are now usually constructed by imbedding a certain number of straight copper wires in gutta percha (Fig. 577), which insulates them from each other; this is surrounded with tarred hemp, and several strands of iron wire are wound outside of all. The copper wires in the interior are the conductors for the transmission of the signals; the gutta percha is for insulation; the hemp and iron are for protection.

Fig. 577. Submarine Cable.

The Atlantic cables contain a central conductor, consisting of seven copper wires, twisted together and covered with three layers of gutta percha, forming altogether a cylinder $\frac{3}{5}$ of an inch in diameter. This is covered with a layer consisting of five strands of hemp, served with a composition consisting of 5 parts of Stockholm tar, 5 of pitch, 1 of linseed-oil, and 1 of bees'-wax. Lastly, the whole is covered by 18 strands of charcoal iron, each strand consisting of seven wires $\frac{7}{10}$ of a millimetre in diameter. On leaving the machine which put on the wire covering the cable was passed through a cauldron containing a mixture of pitch, tar, and linseed-oil. The difficulty of obtaining sufficiently good insulation has thus been completely surmounted.

A second difficulty attaching to submarine telegraphy depends upon the inductive action of the surrounding water, or of the iron sheath. This action, which is found quite sensible in subterranean lines of no great length, becomes of immense importance in long submarine cables. The cable forms one enormous condenser, the central conductor representing the inner coating, and the sea-water, or iron sheath, the outer coating of a Leyden-jar. In the Atlantic cables, the retardation of the signals due to this cause is so considerable that it would be barely possible to obtain a speed one-fifth of that usually attained on land-lines, if the same modes of sending and receiving signals were employed. The electrical capacity of the cable is in fact so enormous, that a long time is required to give it a full charge from a battery, or to discharge it again. The signals accordingly lose all their sharpness, and run into one another, unless special precautions are taken. After sending a current from one pole of the battery, the cable must be discharged, either by putting it to earth, or, still better, by connecting it for an instant with

the other pole of the battery. The residual effects of the first current are thus quickly destroyed, and the line is left free for a second signal.

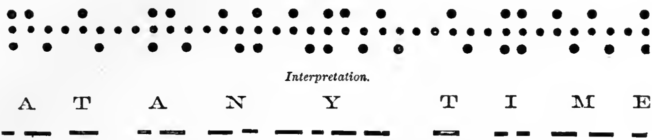
As the first effect received through such a cable is very slight, a very sensitive receiving instrument is necessary for quick working. Thomson's mirror galvanometer (§ 719) is the instrument which was first employed, the signals being read off by an attendant who watches the movements of the spot of light, dots and dashes being represented by deflections in opposite directions. A self-recording instrument by the same inventor is now coming into use, in which the signals are written with ink discharged from a very light glass siphon, the siphon being moved by a very light coil of fine copper wire, suspended by a silk fibre between the poles of a very powerful permanent magnet. The coil turns in one direction or the other according as the current transmitted is positive or negative, thus producing opposite sinuosities in the ink record which is traced upon an advancing strip of paper. The regular flow of the ink is assisted by electrical attraction, on the principle of the bucket or watering-pot described in § 599; but with this difference, that it is not the ink but the paper that is electrified. An electrical machine of peculiar and novel construction, bearing some resemblance to the replenisher of § 644, is employed for this purpose.

849. Wheatstone's Automatic System.—Another very effective contrivance for increasing the speed of signalling, is Wheatstone's automatic apparatus, which is very extensively adopted by the authorities of the postal telegraphs. The first step towards sending a message by this system consists in punching the message in a ribbon of stiff paper. The punching is done by a special instrument, the operator having merely to put down three keys, one of which represents *dot*, another *dash*, and the third *blank*. The holes punched are in three rows. Those in the middle row are equidistant, and are intended to perform the office of the teeth of a rack in guiding the paper uniformly forwards. Those in the two outside rows contain the message, a dot being represented by a pair of holes exactly opposite each other (:) one in each row, and a dash by two holes ranged obliquely (˙.).

The punched strips are then put through the transmitting instrument, and, by regulating the movements of two pins, cause the transmission of the currents necessary for printing the message at the receiving station. From 100 to 150 words are thus transmitted per minute and automatically printed.

The following is a specimen of three consecutive words of a telegraphic message, as it appears on the punched strip at the sending station, and on the printed strip at the receiving station:

As Punched.



As Printed.

The practical limit to speed, in lines of considerable length, arises not so much from the difficulty of making quicker movements, as from the blending together of successive signals in travelling a great distance, especially if part of the distance be under ground or under water. This evil is partly remedied by making each signal consist, not of a single current, but of two; thus a dot will be produced by an instantaneous current, *immediately* succeeded by another of opposite sign; a dash by an equally short current followed *at a longer interval* by an opposite one. In this way, though a greater number of currents are required for each word, a greater number of words can be distinctly signalled in a given time; and, by sending three properly adjusted currents for each signal, a still greater speed of distinct transmission is possible. The transmitting instrument of Wheatstone's automatic system does in fact send three currents for each dot or dash.

850. Duplex Working.—Of late years methods of sending two messages in opposite directions along the same wire at the same time have been very extensively introduced. This mode of operating is called *duplex* telegraphy. It requires that the current sent from either station shall not affect the receiving instrument at that station.

One method of attaining this end depends upon the principle that, if the coil of an electro-magnet be tapped at any point in its length, a current sent into it at this point will traverse the two portions of the coil in opposite directions; whereas a current sent in at either end of the coil traverses the whole of it in one direction. Suppose this coil to be the coil of the electro-magnet which actuates the receiving instrument at any station. The currents from the trans-

mitter at this station are sent into the coil at a point near its middle, and, circulating in opposite directions in its two portions, annul each other's effect upon the core, the arrangements being such that one of these portions forms the inner and the other the outer portion of the whole coil, and that, with equal currents, their effects in magnetizing the core are equal. On the other hand, currents arriving from another station enter at one end of the coil, and circulate round its whole length in one direction.

In order to obtain an exact balance, the two currents which circulate in opposite directions must be equal, and as they are both produced by the same electro-motive force, the resistances in the two partial circuits must be equal. One of these includes the line-wire. The other goes to earth, and on its way thither is made to pass through a resistance which must be adjusted to exact equality with the line-wire. This mode of duplex sending is called the *Differential* method, from a remote resemblance to the differential galvanometer.

Another mode of duplex working is known as the *Bridge* method, because it depends upon the principle of Wheatstone's Bridge.

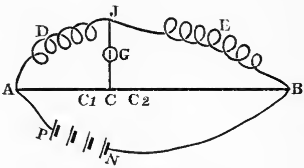


Fig. 578.—Wheatstone's Bridge.

In Fig. 578 (which we here reproduce from § 756) it is allowable to suppose the three conductors which meet at B to be disconnected from each other, and separately put to earth; for this is merely equivalent to keeping the point B at the potential of the earth, and will not affect the difference of potential of any two points.

Let P N be the battery at any station, its pole N being connected to earth by the wire N B, G the receiving instrument at the same station, D, A C, C B three resistances at this station, the point B of C B being to earth, and E the line-wire leading to a distant station, where it finally reaches earth at B. Then by the principle of the bridge, if the four resistances D, E, A C, C B are proportional, the current of the battery will not affect the receiving instrument. On the other hand, the battery at the distant station will affect it, for this battery is in the branch J B, and will always produce a difference of potential between the points J and C, whatever be the relation of the resistances.

When both stations are sending to each other simultaneously, the actual current at any point will be the algebraic sum of the currents due to the two batteries.

It is practically necessary, in most cases, to connect the point C with a condenser, whose capacity should bear the same ratio to that of the line-wire E as the resistance in C B to the resistance in E.

850 A. Quadruplex Telegraphy.—Duplex telegraphy is converted into quadruplex by the following additional device:—

At each station the current passes through two receiving instruments, one of which is only affected by strong currents, while the other is only affected by currents of a particular sign—say positive. A weak positive current will affect the second instrument and not the first, while a strong negative current will affect the first and not the second. There are, accordingly, two sending instruments employed at each station, one sending weak currents of a particular sign, and the other sending strong currents of the opposite sign. This arrangement, combined with one of the duplex arrangements above described, permits the sending of two currents each way at the same time, so that four currents are simultaneously passing through the same wire, producing signals in four separate instruments.

CHAPTER LXI.

MISCELLANEOUS APPLICATIONS OF ELECTRICITY.

851. Electro-magnetic Engines.—Electro-magnetic engines, more briefly styled *electromotors*, are machines driven by currents; their action depending on mechanical forces called out either between magnets and magnets, or between magnets and currents, or between currents and currents. Since their first construction in 1834 by Jacobi of St. Petersburg, who propelled a boat on the Neva by means of one, they have remained in the position of scientific toys till the recent electrical revival; but they are now becoming important in connection with the electrical transmission of driving power to a distance. A waterfall or a fixed steam-engine can be employed to generate a current of electricity by means of a dynamo or other magneto-electric machine, and this current can be made to propel a carriage or drive machinery at a distance by means of an electromotor, which receives the current and reconverts it into mechanical effect. There is always some waste of energy in this double process of conversion; but the waste is less than by any other mode of transmitting power, if the distance be considerable.

The attempts of early inventors to bring such machines, with galvanic batteries supplying their currents, into competition with steam-engines, necessarily resulted in failure, on the score of expense. A current can be more cheaply produced by a steam-engine driving a dynamo machine than by a galvanic battery; and less work would be obtainable from an electromotor driven by this dynamo than from the steam-engine direct.

852.—The most successful electromotors hitherto employed have been continuous-current dynamo machines, such as that of Siemens (Fig. 550), or of Gramme (Fig. 555), used not as dynamo machines but in the converse manner. To explain how the motion is produced, we may begin with a somewhat simpler case—that of the original Siemens' armature depicted in Figs. 545, 546. If a current from without be sent through the coil of this armature so as to make it an electro-magnet with *a* and *b* (Fig. 546) as poles, there will be a dead point in the position represented in the figure, where the fixed pole A of the field magnet is repelling *a* and the other

fixed pole B is repelling b; but if the armature be slightly displaced from this position these two repulsions will concur in rotating the armature through about 180°. By the action of the commutator (Fig. 547) the current is interrupted for an instant at each of the two dead points (which are 180° asunder), and is then again supplied in such a direction that the pole which has just passed a pole of the field magnet is repelled by it, the repulsion lasting till the next interruption of the current. This armature is actually employed in the manner here described for some kinds of light work such as the driving of sewing-machines; but the occurrence of the dead points is a disadvantage. This difficulty could be surmounted by employing two such armatures in positions differing by 90° from each other; but still greater steadiness is obtained by employing the arrangement of Fig. 550, which may be regarded as a combination of a number of such armatures with their poles ranged at equal distances round the circumference of the circle described.

Again in the case of the Gramme ring (Fig. 552) it is clear that if a current were sent into the coil at C from an external source and drawn off at E, this current would divide itself into two parts, one going through CDE and the other through CFE. If we suppose C to be the top and E the bottom, the current both at D and at F will circulate in the direction of watch-hands; hence both halves of the coil combine to give one pole at C and the other at E. The attractions and repulsions between these poles and the poles P P′ of the field magnet will constantly tend to turn the ring in one direction; for instance, if C is similar to P, C will be urged to the right and E to the left.

The rotations in all these cases might also have been deduced from the tendency of wires conveying a current to move across tubes of magnetic force. The two explanations in fact are fundamentally identical.

853. Quantitative Relations.—The following investigation shows the relations which exist between the work employed in driving the generator and the work given out by the motor.

Let E denote the e.m.f. of the *generator* (that is of the dynamo employed to generate the electricity), and e the reverse e.m.f. of the *motor* (which is itself a dynamo worked backwards). The whole e.m.f. in the circuit is $E-e$, and if R denote the whole resistance of the circuit, the expression for the current will be

$$C=\frac{E-e}{R}.$$

In each unit of time the quantity CE of mechanical energy is converted into electrical energy in the generator, and the quantity Ce of electrical is converted into mechanical energy in the motor.

The efficiency, as measured by the ratio of the mechanical energy given out to that put in, is accordingly $\frac{e}{E}$, and the work wasted is C(E$-e$), which, on reference to the value above obtained for C, will be seen to be equal to C^2 R, the well known expression for the heat generated.

The expression for the efficiency shows that for economical working, the reverse e.m.f. should be a large fraction of the direct.

On the other hand, to obtain the greatest amount of work from the motor *in a given time,* when E and R are given, the product $e(E-e)$ must be made a maximum, that is, E must be divided into two parts whose product is the greatest possible; hence the two parts must be equal, e will be $\frac{1}{2}$E, and the efficiency will be $\frac{1}{2}$.

854. Economy in Transmission.—When large quantities of electrical energy are to be transmitted to great distances, whether for driving motors or for supplying electric lamps, it is important that the work spent in heating the intervening conductor should be as small as possible. The expression for this work is C^2r, where r denotes the resistance of the conductor. This latter factor can be diminished by increasing the size of the conductor, but a stout rod of copper is very expensive when the distance is several miles. The other factor C^2 can be diminished without change in the whole amount of energy, if we at the same time increase the electro-motive force E, so as to keep the product CE unchanged in value. If electricity is ever to be transmitted with commercial success over such distances as 50 or 100 miles, it must be by the employment of excessively high electro-motive forces.

The objections to high electro-motive force are the increased tendency to leakage, and the more dangerous character of the shock which will be received by a person inadvertently touching the conductor. From 150 to 200 volts (see page 852) is the limit which the Board of Trade has hitherto imposed on circuits liable to be touched by the public, whereas 2000 to 2500 volts have been advantageously employed in electric light installations. To obtain economy combined with safety, means have been devised for transforming currents of high tension into larger currents of lower tension. This has been done in the three following ways.

854A. Transformation of Currents.—The first method consists in employing the original current to charge storage cells arranged in a long series, and afterwards rearranging them in shorter series.

The second consists in employing the original current to supply an electromotor which drives by mechanical means a low-tension dynamo. The simplest mode of making the connection is to mount the armature of the motor and the armature of the dynamo on the same axle.

These two methods are applicable to direct currents.

In the third method, which is specially applicable to alternate currents, an apparatus is employed consisting of a primary and a secondary coil wound together over an iron core, the secondary consisting of much stouter wire than the primary, and having about the same total weight. The original alternating current is passed through the primary, and generates by induction a larger current of lower tension in the secondary. This apparatus is technically called a *transformer,* and much attention has been given to the improvement of it in recent years. The primary and secondary conductors should be closely interwound, and the iron core should not have free ends, but should form a closed circuit (for magnetic lines of force) embracing the coil. In some of the most efficient transformers it is so extended as almost completely to surround the coil.

It is now a common thing for electricity, like gas, to be supplied to a number of houses through "mains" proceeding from a central station; the "mains" consisting, in this case, of stout copper wires well insulated and laid in pairs, one wire for the direct and the other for the return current. In connection with such systems of electrical supply, it is usual to employ one of the above modes of transformation, the transformer being interposed between the mains and the houses.

855. Froment's Engine.—Of earlier forms of electromotor the best known perhaps is Froment's. It may be described as consisting of a wheel, with eight armatures of soft iron attached to its circumference at intervals of 45°, rotating under the action of four electromagnets fixed to a cast-iron frame at intervals of 60°. Each magnet is "made" when an armature comes within 15° or 20° of it, and "unmade" as the armature is passing it.

The making and breaking of the circuits is effected by means of three distributors, one of which is shown on an enlarged scale in

Fig. 581. R is an eight-toothed wheel, fixed to the axis on which the armatures revolve, and turning with them. Each tooth, as it

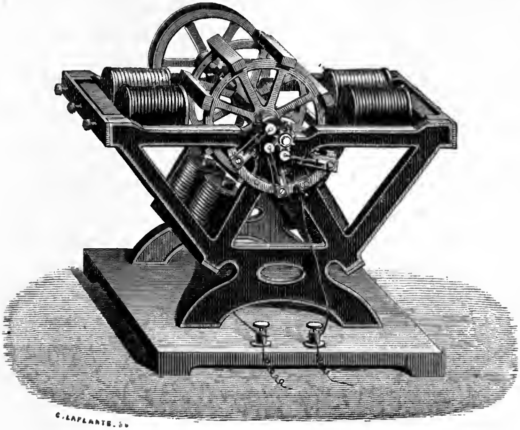


Fig. 580.—Froment's Engine.

passes the roller *r*, pushes it away, and brings the studs *m'm* into contact. As long as they remain in contact, the current circulates through the coil with which the distributor is connected. The distributors are screwed into a metallic arc, which is constantly connected with one pole of the battery. One of them serves for the two opposite horizontal magnets, which are made and unmade together. The two lower magnets have one distributor apiece. Matters are so arranged that the current is not cut off from one coil till just after it has commenced to flow in the next. This precaution prevents, or at least mitigates the induction-spark which generally occurs in breaking circuit (§ 814), and which has the mischievous effect of oxidizing the contacts, and thus, after a time, deranging the movements.

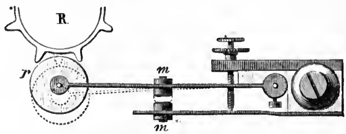


Fig. 581.—Distributor.

856. Edison's Electric Pen.—A good example of the production of mechanical power on a small scale by means of electricity is furnished by Edison's electric pen. A miniature battery sends a current, through a flexible cord consisting of two insulated wires twisted together (one

from each pole of the battery), to a miniature electro-magnetic engine, light enough to be moved about like a pen. The crank of this engine revolves with excessive rapidity, and gives a reciprocating motion to a sharp needle, which moves up and down in a sheath, and projects slightly when at the bottom of its path. The sheath, carrying the engine in its head, is held between the fingers of the writer, and used like a pen, except that it must be held perpendicular to the paper. The writing consists of a series of punctures, through which ink is afterwards passed by means of a roller, the punctured paper thus serving as a stencil-plate.

857. Electrically-controlled Clocks.—Various schemes have been proposed for utilizing electricity in connection with the driving and government of clocks. In some of them, electricity is employed either to wind up the driving-weight, or to fulfil the office of a driving-weight by its own action, a pendulum being employed as the regulator, as in ordinary clocks. In others, electricity both drives and regulates the clock (or even a considerable number of clocks), by means of currents which keep time with the movements of a standard clock, electricity having thus to do the work both of driving and regulating the dependent clocks.

But the system which has given the best practical results is that introduced by Mr. R. L. Jones, in which the dependent clocks are complete clocks, able to go of themselves, and keep moderately good time, without the aid of electricity. The duty devolving on the electric currents is merely to supply the small amount of accelerating or retarding action necessary to prevent the dependent clocks from gaining or losing on the standard clock by whose movements the currents are timed.

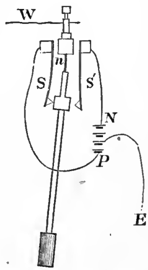


Fig. 582.—Controlling Pendulum.

The arrangements for attaining this end are shown in the annexed figures 582, 583, which represent the pendulums of the controlling and controlled clocks respectively. These pendulums are supposed to be almost precisely of the same length, so that they would nearly synchronize if disconnected.

The controlling pendulum, in its movement to either side, comes in contact with one or the other of two weak springs S S′, which are connected with the poles of a battery P N, having one of its middle plates connected with the

earth, so as to keep its poles at potentials differing from that of the earth in opposite directions. In the position represented in the figure, a current is being sent from the positive pole P into the wire W. When the pendulum swings over to the other side, a negative current will be sent.

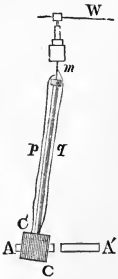


Fig. 583.—Controlled Pendulum.

The bob C C of the controlled pendulum (Fig. 583) is a hollow cylinder of soft iron encircled by a coil, whose ends are connected through two suspending springs at *m* with the wire W and the earth respectively. The consequence of this arrangement is that, whenever a current arrives by the wire W, the bob becomes an electro-magnet.

Two steel magnets A A′ are fixed, with their poles turned opposite ways, in such a position that the hollow bob of the pendulum always encircles one or both of them. Suppose, in the figure, that the poles A A′ which are turned outwards, are the two austral poles, so that the two boreal poles are facing each other. Then matters are to be so arranged that, in the position represented, the pendulum being near the left extremity of its swing, the right-hand end of the coil is a boreal pole, and magnetic force urges the pendulum to the left. When the pendulum is near the right extremity of its swing, the current is in the opposite direction, and consequently the boreal pole of the coil is its left-hand end. The pendulum will thus experience magnetic force urging it to the right. If the pendulum tends to gain upon the standard, its return from the extremities of its swing is thus opposed for a longer time than its outward movement is aided; and if it tends to lose, the assistance to its motion lasts longer than the opposition. Its tendency to deviate from the standard clock either way is thus checked, and the correcting action is greater as the deviation from coincidence is greater. The controlling power thus obtained is so great, that even if the electrical connections are interrupted during several consecutive beats, the accumulated errors will be completely wiped off after the connections are restored.

858. Telephone.—The articulating telephone invented by Professor Graham Bell is represented in Figs. 584, 585. D D is a steel magnet, C a coil of very fine silk-covered copper wire, surrounding the magnet close to one end, and having its terminals in permanent connection with the two binding-screws E E. B B is a thin disc of

soft iron (usually one of the ferrotype plates prepared for photographers), tightly clamped, in its circumferential portion, between the two parts of the wooden case H H, which are held together by

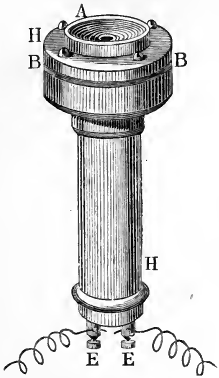


Fig. 584.—Telephone.

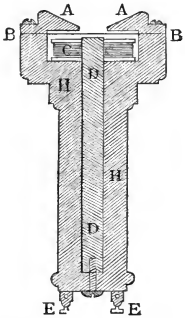


Fig. 585.—Section of Telephone.

screws, while its central portion is left free and nearly touches the end of the magnet. A A is the mouth-piece, through which the speaker directs his voice upon the iron disc.

Two telephones must be employed, one for transmitting, and the other for receiving, one binding-screw of each being connected with the line wire, and the other with the earth or with a return wire, so that their coils form parts of one and the same circuit, and every current generated in the one traverses the other. The mouth-piece A of the receiving telephone is held to the ear of the listener, and he is able to hear the words which are spoken into the transmitting telephone. There is a great falling off in loudness, and a decided nasal twang is imparted, but so much of the original character is preserved that familiar voices can be recognized. Conversations have thus been carried on through 60 or 70 miles of submarine telegraph cable, and through as much as 200 miles of wire suspended in the air on poles.

These results, which came upon the scientific world as a most startling surprise, are explained as follows. The voice of the speaker produces changes of pressure in the air in front of the iron disc, and thus causes the disc alternately to advance and recede,

its movements keeping time with the sonorous vibrations, and the amplitudes of its movements being approximately proportional to those of the particles of air which convey the sound. Now a piece of soft iron, when brought near a magnet, exercises a *quasi* attraction upon the lines of force, causing them to be more closely aggregated in its own neighbourhood, and more widely separated in the other parts of the field. Hence when the disc approaches the magnet, it causes the lines of force to move in towards the axis of the disc, and when it recedes it causes them to open out again.

The lines of force thus cut the convolutions of the coil in opposite directions, according as the disc is approaching or receding, and give rise to alternate currents. These currents, passing through the coil of the receiving telephone, strengthen or weaken, according to their direction, the magnetism of its steel core, and increase or diminish the attraction of the latter for the iron disc. The disc is accordingly set in vibration, and imitates on a diminished scale the movements of the disc of the transmitter. Thus the original sonorous vibrations, having first been converted into undulating currents of electricity, are reproduced as sonorous vibrations. The currents are excessively feeble, probably millions of times feebler than ordinary telegraphic currents; but on the other hand the ear is extremely sensitive to movements however small which recur periodically. Lord Rayleigh has made experiments from which it appears that the note of a whistle is audible at a distance at which the amplitude of the vibrating particles of air is less than a millionth of a millimetre.

When the telephone is employed for conversing through one of a number of telegraphic wires suspended on the same poles, it is found that messages sent by ordinary telegraphic instruments along the other wires are audible in the telephone as a succession of loud taps, so loud in fact as seriously to interfere with the telephonic conversation. This is an illustration of the principle, that the starting or stopping of a current in one wire gives rise to an induced current in a neighbouring wire; but the induced currents in this case, though so loudly audible in the telephone, have never been detected by any other receiving instrument. The telephone appears likely to supplant the galvanometer as a means of detecting feeble currents.

859. Microphone.—Fig. 586 represents one of the best forms of

the microphone of Professor Hughes, the inventor of the printing telegraph which we have described in § 844.

A is a stick of carbon about an inch long, sharpened at both ends, which rest in cavities in the two horizontal supports B B, also of carbon. The upper end of A is free to rattle about in the cavity which contains it, but not to fall away. The two wires E E are in connection respectively with the two supports B B, and are used for putting the instrument into circuit with a receiving telephone at another station. A battery, usually consisting of two or three very small cells, is also introduced into the circuit. The back C in which the supports B B are fixed, and the base D, are of wood, and, besides insulating the carbons, serve to convey to them the sonorous vibrations of the air or of surrounding bodies. These vibrations produce alternate increase and diminution of pressure at the points of contact of the carbons with one another, and as increase of pressure gives closer contact and consequently diminished resistance, the current in the circuit undergoes corresponding changes of strength. These changes act upon the receiving telephone, and cause it to emit sounds which are often much louder than the originals. The microphone in fact acts as a relay, turning on and off the current of the battery, like the Morse relay described in § 843.

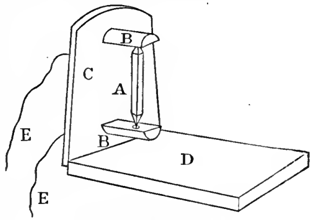


Fig. 586.—Microphone.

The action is improved by employing carbon which has been "metallized" by heating it white hot, and then plunging it in mercury.

The back C should be attached to the base D by a pivot which permits it to be inclined to one side. The best results for speech are usually obtained with an inclination of some 20 or 30 degrees from the vertical. When this inclination is too small there is an increase of noise in the receiving telephone, but a loss of distinctness. A microphone of the above kind transmits spoken sounds with as much distinctness as a telephone, and with much greater loudness. It has also a surprising power of transmitting very faint sounds produced by rubbing or striking the base or back with light bodies. Sounds of this kind which are quite inaudible at the place

where they are produced, are easily heard by a person with his ear to the receiving telephone.

860. Telephonic Transmitters.—Though Bell's original telephone is still used as a receiving instrument, it has been almost entirely superseded as a transmitter by various forms of the microphone on the following plan.

There is a funnel for receiving the voice and converging the waves of sound upon a thin iron diaphragm, as in Bell's telephone. This diaphragm, by its vibrations to and fro, increases and diminishes the pressure at one or more points of contact in a local circuit containing a small battery and the primary coil of a miniature Ruhmkorff. The secondary coil of the Ruhmkorff is connected to the line wire which leads to the receiving instrument.

861. Hughes' Induction Balance.—Bell's telephone, as above stated, is an extremely sensitive indicator of the currents induced in a wire by the commencement or cessation of currents in a neighbouring wire. Professor Hughes has taken advantage of this property to construct a very sensitive instrument for the instantaneous testing of metals.

A current from two or three cells is sent through two small primary coils at a considerable distance apart. Near to them are placed two secondary coils, in circuit with a telephone, and so arranged that the induced currents in them are opposite. When the induced currents are exactly equal they destroy one another; and the adjustments are first made so as to obtain this result, that is, so as to obtain no sound in the telephone when the primary circuit is momentarily made and broken. The balance is then ready for making comparisons. Within each secondary coil is a box for containing the specimens to be compared. If precisely similar specimens are placed in the two boxes, no effect is obtained; but the slightest difference suffices to disturb the balance of the two currents and give a sound. A counterfeit coin can thus be easily distinguished from a genuine one; and even two genuine coins of the same kind will disturb the balance if one is a little more worn than the other. The best conducting metals give the most powerful effects, and a piece of wire gives a very much stronger effect when its ends touch so as as to form a closed circuit than when they are apart. The effect of iron is exceptional, depending partly on currents induced in it and partly on its magnetic properties. Some successful attempts have been made, by Professor Chandler Roberts of the Mint, to apply the instrument to the testing of alloys.

862. Electric Light.—When two pointed pieces of a conducting kind of carbon, such as that which is deposited in the retorts at gas-works, are connected with the poles of a powerful battery, as in Fig. 587, a brilliant light is obtained by bringing them together so as to allow discharge to take place between them. This discharge, when once obtained, will not be interrupted by separating the points to some distance,—greater in proportion to the electro-motive force of the

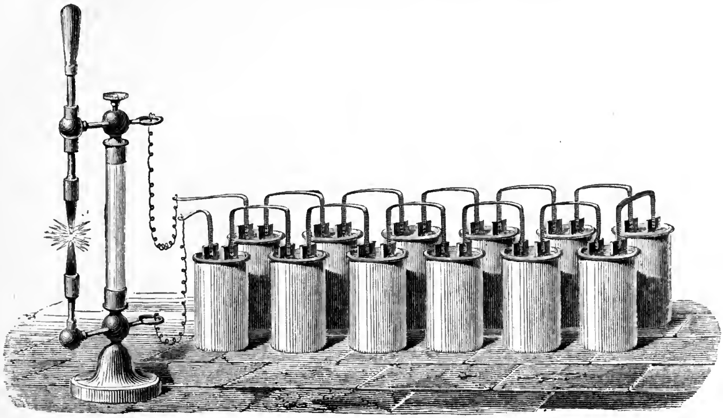


Fig. 587.—Electric Light.

battery; and the interval will be occupied by a luminous arch (known as the *voltaic arc*) of intense brightness and excessively high temperature. This brilliant experiment was first performed by Sir Humphry Davy, at the commencement of the present century, with a battery of 3000 cells. The light appears to be mainly due to the incandescence of particles of carbon which traverse the space between the points.

This transport of particles can be rendered visible to a large number of spectators by throwing an image of the heated points on a screen with the aid of a lens. Fig. 588 represents the image thus obtained, the natural size of the carbons being indicated by the sketch at the right hand. On watching the image for some time, incandescent particles will be observed traversing the length of the arc, sometimes in one direction and sometimes in the other, the prevailing direction being, however, that of the positive current. This circum-

stance, which appears to be connected with the higher temperature of the positive terminal, explains the difference between the forms assumed by the two carbons. The point of the positive carbon becomes concave, while the negative carbon remains pointed and

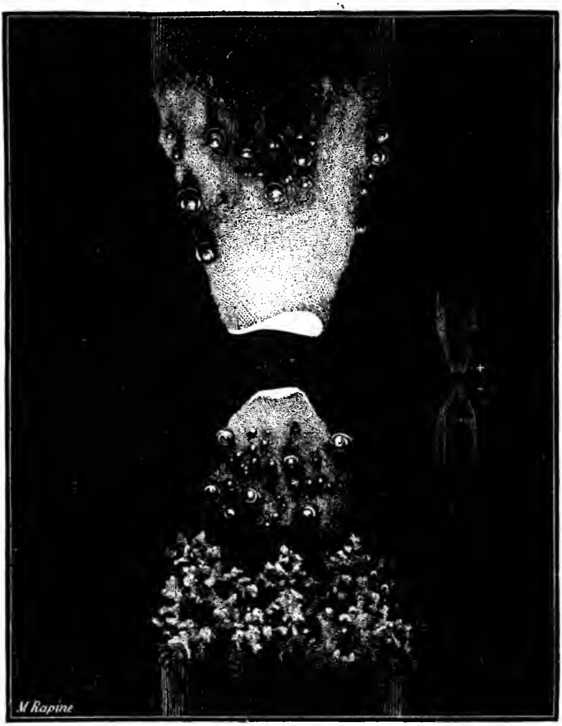


Fig. 588.—Image of the Carbon Points.

wears away less rapidly. This difference is more precisely marked when the experiment is performed *in vacuo;* a kind of cone then grows up on the negative carbon, while a conical cavity is formed in the positive carbon. These phenomena are less clearly exhibited in air, on account of the combustion occasioned by the presence of oxygen.

The voltaic arc exceeds in temperature as well as in brightness all other artificial sources of heat. Despretz succeeded by its means in fusing and even volatilizing many substances which had previously proved refractory. Carbon itself was softened and bent, welded, and apparently reduced to vapour, which was condensed, in the form of black crystalline powder, on the walls of the containing vessel.

The voltaic arc must be regarded as an instance of conduction rather than of disruptive discharge, the air being rendered a conductor by the high temperature to which it is raised. Hence it is that, although discharge does not commence between the points till they have been brought close together, it is not interrupted by subsequently removing them to a considerable distance.

The voltaic arc is acted on by a magnet, according to the same laws as any other current. M. Quet, by employing a very powerful electro-magnet, with its poles at equal distances on opposite sides of the line joining the points, repelled the arc laterally to such an extent that it resembled a blowpipe flame (Fig. 589).

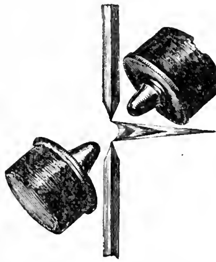


Fig. 589.—Action of Magnet on Voltaic Arc.

863. Character of the Light.—The light of the voltaic arc has a dazzling brilliancy, and attempts were long ago made to utilize it. The failures of these attempts were due not so much to its greater costliness in comparison with ordinary sources of illumination, as to the difficulty of using it effectively. Its brilliancy is painfully and even dangerously intense, being liable to injure the eyes and produce headaches. Its small size detracts from its illuminating power—*it dazzles rather than illuminates*—and it cannot be produced on a sufficiently small scale for ordinary purposes of convenience. There is no mean between the absence of light and a light of overpowering intensity.

There is, however, one application in which these peculiarities of the electric light are positive advantages, penetration being the essential requisite; we mean the lighting-up of lighthouses. Here the office of the light is not to render other objects visible, but to be itself seen; and in this respect, in hazy weather, the electric light is found decidedly superior to oil-lamps.

The electric light has also long been used for throwing images on a screen in lecture-illustrations, and for producing various luminous effects in theatrical exhibitions.

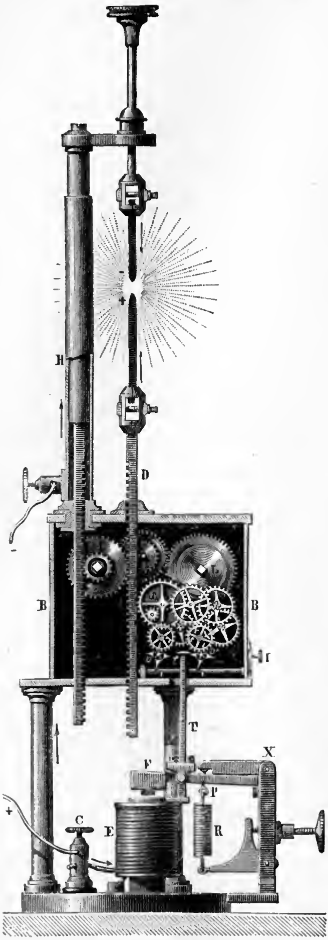


Fig. 590.—Foucault's Regulator.

As the carbons undergo waste by combustion, it is necessary to employ some means for keeping them at a nearly constant distance, so as to give a steady light. Several different regulators have been employed for this purpose, all of them depending on the principle that the strength of the current diminishes, as the distance, and consequently the resistance, increases. We will briefly describe Foucault's.

864. Foucault's Regulator.—It contains two systems of wheelwork, one for bringing the carbons nearer together, and the other for moving them further apart. Fig. 590 represents the apparatus, with the omission of a few intermediate wheels. L′ is a barrel driven by a spring inclosed within it, and driving several intermediate wheels which transmit its motion to the fly *o*. L is the second barrel, driven by a stronger spring, and driving in like manner the fly *o*′. The racks which carry the carbons work with toothed wheels attached to the barrel L′, the wheel for the positive carbon having double the diameter of the other, because experience has shown that it is consumed twice as rapidly. The current enters

at the binding-screw C, traverses the coil of the electro-magnet E, and passes through the wheel-work to the rack D, which carries the positive carbon. From the positive carbon it passes through the voltaic arc to the negative carbon, and thence, through the support H, to the binding-screw connected with the negative pole of the battery.

When the armature F descends towards the magnet, the other arm of the lever F P is raised, and this movement is resisted by the spiral spring R, which, however, is not attached to the lever in question, but to the end of another lever pressing on its upper side and movable about the point X. The lower side of this lever is curved, so that its point of contact with the first lever changes, giving the spring greater or less leverage according to the strength of the current. In virtue of this arrangement, which is due to Robert Houdin, the armature, instead of being placed in one or the other of two positions, as in some other regulators, has its position continuously varied according to the strength of the current. The anchor T t is rigidly connected with the lever F P, and follows its oscillations. If the current becomes too weak, the head t moves to the right, stops the fly o' and releases o, which accordingly revolves, and the carbons are moved forward. If the current becomes too strong, o is stopped, o' is released, and the carbons are drawn back. When the anchor T t is exactly vertical, both flies are arrested, and the carbons remain stationary. The curvature of the lever on which the spring acts being very slight, the oscillations of the armature and anchor are small, and very slight changes in the strength of the current and brilliancy of the light are immediately corrected.

865. Jablochkoff's System of Electric Lighting.—The modern revival of interest in the electric light dates from the Paris Exhibition of 1878; when some of the streets of Paris were for the first time lighted by electric lamps constructed on a plan devised by M. Jablochkoff. Instead of placing the two carbons end to end, and providing mechanism for keeping them at the proper distance, he dispenses with mechanism, and places them side by side, with an insulating substance between them, which is gradually consumed. A A (Fig. 591) are the two carbons, separated by a stick of plaster of Paris B. The heat produced by the electric current fuses the plaster of Paris between the points of the carbons, and the fused portion acts as a conductor of high resistance, becoming brightly

incandescent. To light the lamp, a piece of carbon, held by an insulator, is laid across the two carbon points until the light appears, and is then removed. The lower ends of the carbons are inserted in copper or brass tubes C C, separated from each other by asbestos; and these tubes are connected by binding-screws with the two wires which convey the current.

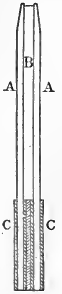


Fig. 591. Jablochkoff Candle.

When the current employed flows always in the same direction, the positive carbon is made twice as large in section as the negative, because it is consumed about twice as fast. When the current is alternating, which is the preferable arrangement, they are made equal.

The light, when used for street lamps, is surrounded by a globe of opal glass, which serves to diffuse its intensity and prevent dazzling.

The current is furnished by a magneto-electric machine, either an ordinary Gramme machine, which gives a current always in one direction, or a Gramme machine specially modified for giving currents in alternate directions. The machine is driven by a small steam or gas engine of as many horse-power as there are lamps to be supplied; sixteen lamps being sometimes supplied in one circuit by a single machine.

865A. Incandescent Lamps.—Another form of electric light more suitable for domestic purposes, because far steadier and less dazzling, is now coming into favour. A filament of carbon prepared from bamboo, paper, or some other fibrous material, and about as thick as sewing thread, is inclosed within a vacuous glass vessel, its two ends being attached to wires which pass through the base of the lamp and serve as electrodes. A current of proper strength heats the carbon filament to whiteness, causing it to emit a soft and brilliant light, and the carbon is not consumed, as there is no oxygen to produce combustion. The vacuum must be the most perfect that can be obtained with the best Sprengel pump. One of the best known of these lamps is represented in Fig. 591A. The thin black line in the interior represents the carbon filament, which is highly elastic and takes two turns at its upper end.

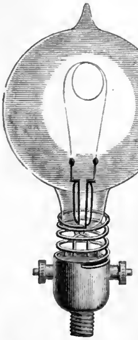


Fig. 591A.—Swan's Incandescent Lamp.

APPENDIX.

ELECTRICAL AND MAGNETIC UNITS.

UNITS AND DERIVED UNITS.

(1.) The numerical value of a concrete quantity is its ratio to a particular unit of the same kind; the selection of this unit being always more or less arbitrary.

(2.) One kind of quantity may, however, be so related to two or more others, as to admit of being specified in terms of units of these other kinds. For example, of the three kinds of quantity, called distance (or length), time, and velocity, any one is capable of being expressed in terms of the other two. Velocity can be specified (as regards amount) by stating the distance passed over in a specified time. Distance can be specified by stating the velocity required for describing it in a specified time, and time can be specified by stating the distance described with a specified velocity.

Force, distance, and work are in like manner three kinds of quantity, of which any two are just sufficient to specify the third.

(3.) Calculation is greatly facilitated by employing as few original or underived units as possible. These should be of kinds admitting of easy and accurate comparison; and all other units should be derived from them by the simplest modes of derivation which are available.

DIMENSIONS.

(4.) Velocity is proportional directly to distance described, and inversely to the time of its description; and is independent of all other elements. This is expressed, by saying that *the dimensions of velocity* are $\frac{\text{distance}}{\text{time}}$ or $\frac{\text{length}}{\text{time}}$.

Again, if we define the unit of velocity to be that with which unit distance would be described in unit time, the real magnitude of the unit of velocity will depend upon the units of length and time selected, being proportional directly to the real magnitude of the former, and inversely to the real magnitude of the latter. This is expressed by saying that *the dimensions of the unit of velocity* are $\frac{\text{length}}{\text{time}}$. Both forms of expression are convenient; and the ideas which they are intended to express are logically equivalent.

MECHANICAL UNITS.

(5.) All electrical and magnetic units can be derived from units of length, mass, and time. We shall denote length by l, mass by m, and time by t.

(6.) The unit of *velocity* is the velocity with which unit length is described in unit time. Its dimensions are $\frac{l}{t}$.

(7.) The unit of *acceleration* is the acceleration which gives unit increase of velocity in unit time. Its dimensions are $\frac{\text{velocity}}{\text{time}}$ or $\frac{l}{t^2}$.

(8.) The unit *force* is that which acting on unit mass produces unit acceleration. Its dimensions are mass $\times$ acceleration, or $\frac{m\,l}{t^2}$.

(9.) The unit of *work* is the work done by unit force working through unit length. Its dimensions are force $\times$ length, or $\frac{m\,l^2}{t^2}$.

(10.) The unit of *kinetic energy* is the kinetic energy of *two* units of mass moving with unit velocity (according to the formula $\frac{1}{2}\,m\,v^2$). Its dimensions are mass $\times$ (velocity)^2, or $\frac{m\,l^2}{t^2}$, and are the same as the dimensions of work. It might appear simpler to make it the energy of *one* unit of mass moving with unit velocity; but if this change were made, it would be necessary either to halve the unit of work, or else to make kinetic energy double of the work which produced it. Either of these alternatives would involve greater inconvenience and complexity than the selection made above.

ELECTRO-STATIC UNITS.

(11.) Let q denote *quantity* of electricity measured statically, so that the mutual repulsion of two equal quantities q at distance l,

is $\frac{q^2}{l^2}$. This being equal to a force, the dimensions of q^2 must be (length)^2 × force, or $\frac{ml^3}{t^2}$, and the dimensions of q must be $\frac{m^{\frac{1}{2}}l^{\frac{3}{2}}}{t}$.

(12.) Let V denote *difference of potential.* Then the work required to raise a quantity q through a difference of potential V, is q V. The dimensions of V are therefore $\frac{\text{work}}{q}$, or $\frac{ml^2}{t^2}\frac{t}{m^{\frac{1}{2}}l^{\frac{3}{2}}}$, or $\frac{m^{\frac{1}{2}}l^{\frac{1}{2}}}{t}$. The dimensions of potential are of course the same as those of difference of potential.

(13.) The *capacity* of a conductor is the quotient of the quantity of electricity with which it is charged, by the potential which this charge produces in the conductor. The dimensions of capacity are therefore $\frac{m^{\frac{1}{2}}l^{\frac{3}{2}}}{t} \cdot \frac{t}{m^{\frac{1}{2}}l^{\frac{1}{2}}}$, or simply l. In fact, as we have seen (§ 613), the capacity of a spherical conductor is equal to its radius.

ELECTRO-MAGNETIC UNITS.

(14.) Let P denote the numerical value of a *pole* (or the strength of a pole). Then, since two equal poles P at distance l repel each other with the force $\frac{P^2}{l^2}$, which must be of the dimensions $\frac{ml}{t^2}$, the dimensions of P are $\frac{m^{\frac{1}{2}}l^{\frac{3}{2}}}{t}$.

(15.) Let I denote the *intensity of* a magnetic *field.* Then, a pole P in this field is acted on with a force P I. This must be of the dimensions $\frac{ml}{t^2}$. Hence, the dimensions of I are $\frac{ml}{t^2} \cdot \frac{t}{m^{\frac{1}{2}}l^{\frac{3}{2}}}$, or $\frac{m^{\frac{1}{2}}}{l^{\frac{1}{2}}t}$.

(16.) Let M denote the *moment* of a magnet. Since it is the product of the strength of a pole by the distance between two poles, its dimensions are $\frac{m^{\frac{1}{2}}l^{\frac{5}{2}}}{t}$.

(17.) Intensity of *magnetization* is the quotient of moment by volume. Its dimensions are therefore $\frac{M}{l^3}$ or $\frac{m^{\frac{1}{2}}}{l^{\frac{1}{2}}t}$. These are the same as the dimensions of intensity of field.

(18.) When a magnetic substance is placed in a magnetic field, it is magnetized by induction; and each substance has its own specific *coefficient of magnetic induction* (constant, or nearly so, when the field is not excessively intense), which expresses the ratio of the intensity of the induced magnetization to the intensity of the

field. For diamagnetic substances, this coefficient is negative, that is to say, the induced polarity is reversed, end for end, as compared with that of a paramagnetic substance placed in the same field.

(19.) The work required to move a pole P from one point to another, is the product of P by the difference of the magnetic potentials of the two points. Hence, the dimensions of *magnetic potential* are $\frac{m\,l^2}{t^2}\,\frac{t}{m^{\frac{1}{2}}\,l^{\frac{3}{2}}}$ or $\frac{m^{\frac{1}{2}}\,l^{\frac{1}{2}}}{t}$.

(20.) A *current* C flowing along a circular arc, produces at the centre of the circle an intensity of field equal to C multiplied by length of arc divided by square of radius. Hence, C divided by a length is equal to a field-intensity, the dimensions of which are $\frac{m^{\frac{1}{2}}}{l^{\frac{1}{2}}\,t}$, and the dimensions of C are $\frac{m^{\frac{1}{2}}\,l^{\frac{1}{2}}}{t}$.

(21.) The *quantity* Q of electricity conveyed by a current is the product of the current by the time that it lasts. Its dimensions are therefore $m^{\frac{1}{2}}\,l^{\frac{1}{2}}$.

(22.) The work done in urging a quantity Q by an electro-motive force E is E Q, hence the dimensions of *electro-motive force* are $\frac{m\,l^2}{t^2}\,\frac{1}{m^{\frac{1}{2}}\,l^{\frac{1}{2}}}$ or $\frac{m^{\frac{1}{2}}\,l^{\frac{3}{2}}}{t^2}$; and as electro-motive force is difference of potential, these are also the dimensions of *potential*.

(23.) The *capacity* of a conductor is the quotient of quantity of electricity by potential; its dimensions are therefore $\frac{t^2}{l}$.

(24.) The *resistance* R of a circuit is, by Ohm's law, equal to $\frac{\mathrm{E}}{\mathrm{C}}$. Its dimensions are therefore $\frac{m^{\frac{1}{2}}\,l^{\frac{3}{2}}}{t^2}\,\frac{t}{m^{\frac{1}{2}}\,l^{\frac{1}{2}}}$ or $\frac{l}{t}$, and are the same as the dimensions of velocity.

COMPARISON OF THE TWO SETS OF UNITS.

(25.) On comparing the dimensions of the same element as measured according to the two systems, it will be observed that they are not identical. The dimensions of quantity of electricity, for example, in the first system, are to its dimensions in the second, as l to t; and the dimensions of capacity are as l^2 to t^2.

Notwithstanding this difference of dimensions, two quantities of electricity which are equal when compared statically, are also equal when compared magnetically, or if one be double of the other when

compared statically, it will also be double of the other when compared magnetically.

(26.) An illustration from a somewhat more familiar department may assist the reader in convincing himself that it is possible for one and the same kind of quantity to have different dimensions according to the line of derivation employed. It is well known that uniform spheres attract each other with a force which is directly as the product of their masses, and inversely as the square of the distance between their centres. If this law were made to furnish the unit of force, the dimensions of force would be $\frac{m^2}{l^2}$, instead of $\frac{ml}{t^2}$, as previously found. The ambiguity depends partly on the fact that l in the one formula denotes distance between attracting centres, and in the other distance moved over. It is only when the mode of derivation is distinctly specified, or is too obvious to need specification, that the dimensions of a quantity admit of being determinately stated. As the definition of a derived unit necessarily involves a specification of the mode of its derivation, there is some advantage in speaking of the *dimensions of a unit*, rather than of the dimensions of the quantity which the unit serves to measure.

(27.) Derived units are often called *absolute* units; but it seems an abuse of language to define a unit by its *relation* to other arbitrary units, and then call it *absolute*.

(28.) A committee of the British Association have recommended that the centimetre, gramme, and second be adopted as the general basis of all derived units; and that the units thence derived be distinguished by the initial letters C. G. S. prefixed.

(29.) Ratio of the Two Units of Quantity is the Velocity of Light.—Let the units of length, mass, and time in any other system be respectively equal to

l centimetres, m grammes, t seconds.

Then the new electro-magnetic unit of *quantity* will be $m^{\frac{1}{2}} l^{\frac{1}{2}}$ times the C. G. S. electro-magnetic unit; and the new electro-static unit of quantity will be $m^{\frac{1}{2}} l^{\frac{3}{2}} t^{-1}$ times the C. G. S. electro-static unit. If the two new units of quantity are *equal*, we shall have the following relation between the two C. G. S. units, namely—

$$m^{\frac{1}{2}} l^{\frac{1}{2}} \text{ electro-magnetic units} = m^{\frac{1}{2}} l^{\frac{3}{2}} t^{-1} \text{ electro-static units};$$

that is,

$$\frac{\text{C. G. S. electro-magnetic unit}}{\text{C. G. S. electro-static unit}} = \frac{l}{t}.$$

But $\frac{l}{t}$ is clearly the value, in centimetres per second, of that velocity which would be called unity in the new system. This is a definite concrete velocity; and its numerical value will always be equal to the ratio of the electro-magnetic to the electro-static unit of quantity, whatever units of mass, length, and time are employed.

From numerous experiments in which the same quantity of electricity was measured both statically and magnetically, it appears that this velocity is (within the limits of experimental error) identical with the velocity of light. Professor Clerk Maxwell maintains that light, electricity, and magnetism are all affections of one and the same medium; that light is an electro-magnetic phenomenon, and that its laws can be deduced from those of electricity and magnetism.

The following resolutions were adopted at the International Congress of Electricians at Paris in 1881:—

1. For electrical measurements, the fundamental units, the centimetre (for length), the gramme (for mass), and the second (for time), are adopted.

2. The Ohm and the Volt (for practical measures of resistance and of electromotive force or potential) are to keep their existing definitions, 10^9 for the Ohm, and 10^8 for the Volt.

3. The Ohm is to be represented by a column of mercury of a square millimetre section at the temperature of zero Centigrade.

4. An International commission is to be appointed to determine, for practical purposes, by fresh experiments, the length of a column of mercury of a square millimetre section which is to represent the Ohm.

5. The current produced by a Volt through an Ohm is to be called an Ampère.

6. The quantity of electricity given by an Ampère in a second is to be called a Coulomb.

7. The capacity defined by the condition that a Coulomb charges it to the potential of a Volt is to be called a Farad.

As regards the 4th item, it was decided two years later that 106 centimetres should be adopted as the length of the column. A more accurate value is 106·3 centimetres.

EXAMPLES.

1. Sum to infinity the two geometric series of § 622, which express the quantities successively discharged from the two coatings.

2. Compare the energy of discharge of a single Leyden-jar with that of a battery of n such jars,

(1) When the charge of the single jar is equal to that of the battery,

(2) When both are charged to the same potential.

3. A series of n Leyden-jars are charged by cascade, the knob of the first being in connection with the conductor of the machine, the potential of which is V. If the first jar be disconnected from the machine and from the second jar, and its outer coating be connected with the earth, what will be the potential of its inner coating?

4. Show that the spark obtained by connecting the knob of the first jar in a cascade arrangement with the outer coating of the last, will be stronger than that which would be obtained by connecting the knob and outer coating of the first jar, if this jar were charged in the ordinary way with the same quantity of electricity which it has in the cascade arrangement.

5. If n similar jars are charged by cascade, and then connected so as to form an ordinary Leyden-battery, compare the energy of the discharge obtained by connecting the two coatings of the battery with that of the discharge which would have been obtained by connecting the inner coating of the first jar with the outer coating of the last in the cascade arrangement.

6. An electrified body is fixed at the distance of a few inches from the knob of an uncharged gold-leaf electroscope, and produces divergence of the leaves. How will this divergence be affected,

(1) By introducing a wire-gauze shade in connection with the earth between the charged body and the electroscope?

(2) By placing a wire-gauze shade in connection with the earth so as to inclose both the charged body and the electroscope?

7. A metallic vessel A is filled with shot, which run out, one by one, along a metal tube terminating near to an insulated positively charged conductor, but not so near that a spark can pass. The shot drop from the tube into a second metallic vessel B. What will be the final electrical condition of each of the vessels;

(1) If both are insulated?

(2) If B is insulated, but not A?

(3) If A and B are connected together by a wire, but insulated from other bodies?

Show how the principle of the conservation of energy applies in each case.

8. Show that the energy of a conductor of capacity C charged to potential V is $\frac{1}{2}CV^2$.

9. Show that the gain or loss of potential energy in transferring a quantity Q of electricity from one conductor to another is $Q(V_1 - V_2)$, where V_1 is the arithmetical mean of the potentials of one of the two conductors before and after the transfer, and V_2 is the similar mean for the other conductor.

In the four following examples the skeletons are supposed to be made of uniform wire, and the resistance of one side (or one edge) is called unity.

10. Find the resistance between opposite corners of a skeleton square.

11. Find the resistance between two corners of a skeleton equilateral triangle.

12. Find the resistance between two opposite corners of a skeleton cube.

13. Find the resistance between two corners of a skeleton regular tetrahedron.

14. Investigate a formula for the resistance of a wire in terms of its length, mass, density, and specific resistance.

15. The terminals of a battery of three cells are connected by a wire of resistance R; and it is found that when the terminals of a fourth cell similar to the cells of the battery are connected with the terminals of the battery, the current through R is not altered. Compare R with the resistance of one cell.

16. A battery consists of ten similar cells arranged in a series, and the circuit is completed by a wire 10 ft. long. If this wire, at a point 2 ft. from the first terminal, is allowed to touch the binding-screw which connects the second and third cells, show whether there will be any alteration in the current in either part of the wire.

17. The terminals of a battery are connected by a wire of ten thousand units' resistance. Compare the indications of an electrometer when its electrodes are joined (1) to the terminals of the battery, (2) to points in the wire separated by eight thousand units' resistance, (3) to points separated by three thousand units' resistance.

18. A galvanic battery of ten cells has its ends joined by a wire 100 ft. long with a resistance five times that of the battery. Also the junction of the third and fourth cells is in communication with the earth. Find the potentials of the other junctions, and of the terminals of the battery.

19. Investigate the effect on the current of a battery of five cells, with an external resistance equal to that of one cell,

(1) When half the liquid in one of the cells is removed,

(2) When, for the zinc of one cell another metal is substituted, such that this cell by itself would produce a current only half that of one of the other cells by itself.

20. A battery is to be constructed with plates of a given aggregate area, and at a given distance apart, for the purpose of heating a wire whose resistance is given. Find the number of cells which will heat the wire most.

21. A and B are two batteries constructed of the same materials. The resistance of A is to that of B as $a : b$, and the current in A is to that in B as $i : j$, the external resistances being negligible. Find the ratio of the amount of zinc consumed in A to that consumed in B in the same time.

22. The current from a battery of ten equal elements, passes through a voltameter, and evolves 50 cc. of hydrogen per minute. Fifty metres of wire are now introduced, in addition, into the circuit, and the volume of hydrogen now evolved in the voltameter per minute is 30 cc. If the resistance of 2·5 metres of the

introduced wire be the unit of resistance, and the unit of current be that which evolves 1 cc. of hydrogen per minute, what is the electro-motive force of one element of the battery?

23. The circuit of a constant battery includes a tangent galvanometer, and an electro-magnetic engine (say a reversed Gramme). Describe and explain the difference, if any, in the indications of the galvanometer, according as the electro-magnetic engine is held at rest, or allowed to turn.

24. A straight horizontal copper bar, in electric communication with the earth by chains hanging vertically from its two ends, is carried in a horizontal plane in the four following ways,

(1) The bar is in the magnetic meridian, and is carried in the direction of its own length.

(2) It is perpendicular to the meridian, and is carried in the direction of its own length.

(3) It is in the meridian, and is carried perpendicular to its own length.

(4) It is perpendicular to the meridian, and is carried perpendicular to its own length.

Compare the currents (if any) generated by the motion in the four cases.

25. A metal ring rotates uniformly round a horizontal diameter, which is perpendicular to the magnetic meridian. In what parts of the revolution is the induced current strongest, and in what parts does it vanish?

26. Compare the currents in the preceding question with those induced by rotating the ring with the same velocity round a vertical diameter.

27. Compare the electro-motive forces generated, in two rings of different radii, by rotating with equal angular velocities round parallel diameters.

28. Prove that the distance of a fault in a submarine cable is to the whole length of the cable as

$$S - \sqrt{(T-S)(R-S)} \text{ to } R,$$

S denoting the resistance of the faulty cable when connected with earth at the further end,

T its resistance when insulated at the further end,

R the resistance of the cable before it was faulty. The fault is supposed to consist in a loss of insulation, and all parts of the cable except the fault are supposed to be perfectly insulated.

ANSWERS.

Ex. 1. Q, mQ. Ex. 2. Energy of discharge of single jar is n times that of battery in case (1), and $\frac{1}{n}$ in case (2). Ex. 3. $\frac{V}{n}$.

Ex. 4. Since Q is to equal Q′, the charges and potentials in the cascade arrangement are n times as great as in the case supposed in § 632. Hence the energy of the spark is n^2 times as great. It is therefore n times the energy of the spark of the single jar. Ex. 5. The same.

Ex. 6. In case (1) the electroscope will be completely screened from the influence of the electrified body, and the leaves will collapse. In case (2) electricity of the opposite sign to that of the charged body will be induced on the shade, and the divergence of the leaves will be diminished.

Ex. 7. (1) A will become positively and B negatively charged, the shots acting as carriers of negative electricity from A to B. (2) B will become negatively charged, more quickly than in case (1). (3) The negative carried from A to B by the shots returns from B to A by the wire as fast as it is supplied.

In (1) and (2) the descent of the shots is opposed by electrical forces. Hence they fall more gently, and generate less heat by concussion, than they would in the absence of electricity.

Ex. 10. 1. Ex. 11. $\frac{2}{3}$. Ex. 12. $\frac{5}{6}$. Ex. 13. $\frac{1}{2}$. Ex. 14. $\frac{\rho l^2 d}{m}$.

Ex. 15. R is $1\frac{1}{2}$ times the resistance of one cell.

Ex. 16. None; for the two points which touch had the same potential before contact.

Ex. 17. As 10, 8 and 3.

Ex. 18. First terminal $\frac{15}{6}e$, last terminal $-\frac{35}{6}e$, junctions $\frac{10}{6}e, \frac{5}{6}e, 0, -\frac{5}{6}e, -\frac{10}{6}e$, &c., e being electro-motive force of one cell.

Ex. 19. The current will be diminished (1) as 7 to 6, (2) as 10 to 9.

Ex. 20. Let R denote the resistance of the wire, and r the resistance of the battery when consisting of a single cell. The number of cells n must be that which gives the smallest difference between nr and $\frac{R}{n}$.

Ex. 21. As ai^2 to bj^2.

Ex. 22. $150 + \frac{1}{10}e'$, where e' denotes the reverse electro-motive force of the volta-meter.

Ex. 23. The current will be weakened by allowing the engine to turn, because the motion generates a reverse electro-motive force.

Ex. 24. No current in cases (1), (2), and equal currents in (3), (4). The currents are due solely to the vertical magnetic force, for though the lines of horizontal force are cut by the chains in (2) and (3), the electro-motive forces are *up* both chains, or *down* both, and so destroy each other.

Ex. 25. Strongest when the plane of the ring is parallel to the dipping-needle. Vanishes when plane of ring is perpendicular to dipping-needle.

Ex. 26. As total intensity to horizontal intensity, or as 1 to cosine of dip.

Ex. 27. As the squares of the radii, or directly as the areas inclosed.

INDEX TO PART III.

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